Constraining cosmology and astrophysics using the combination of CMB and LSS data

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LBL INPA seminar, Sept 16 2022

Part I: Joint cosmological constraints from the SPTxDES 6x2pt analysis

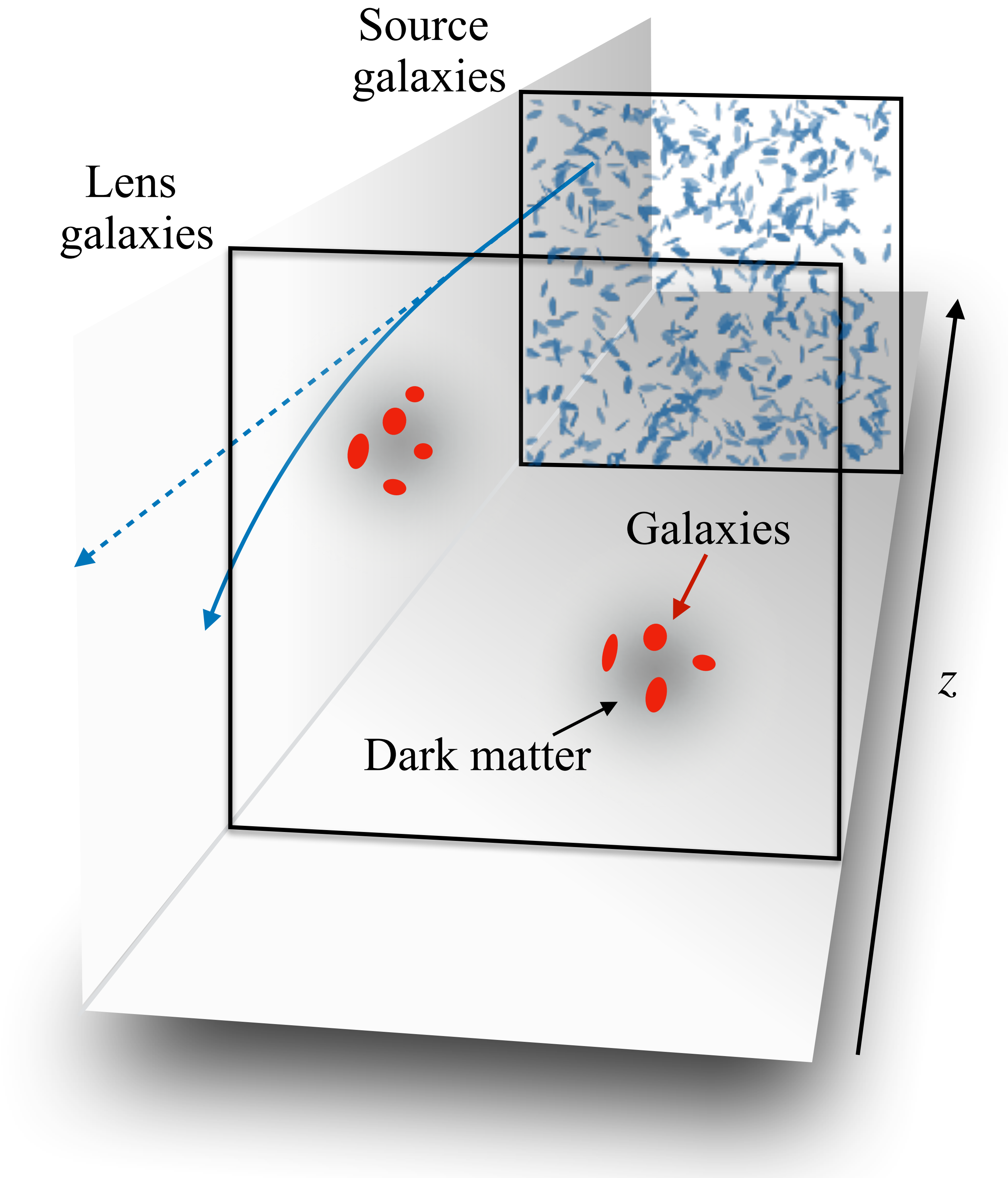
Based on:
https://arxiv.org/abs/2203.12439 (Methodology paper)
https://arxiv.org/abs/2203.12440 (Measurements paper)
https://arxiv.org/abs/2206.10824 (Cosmology paper)

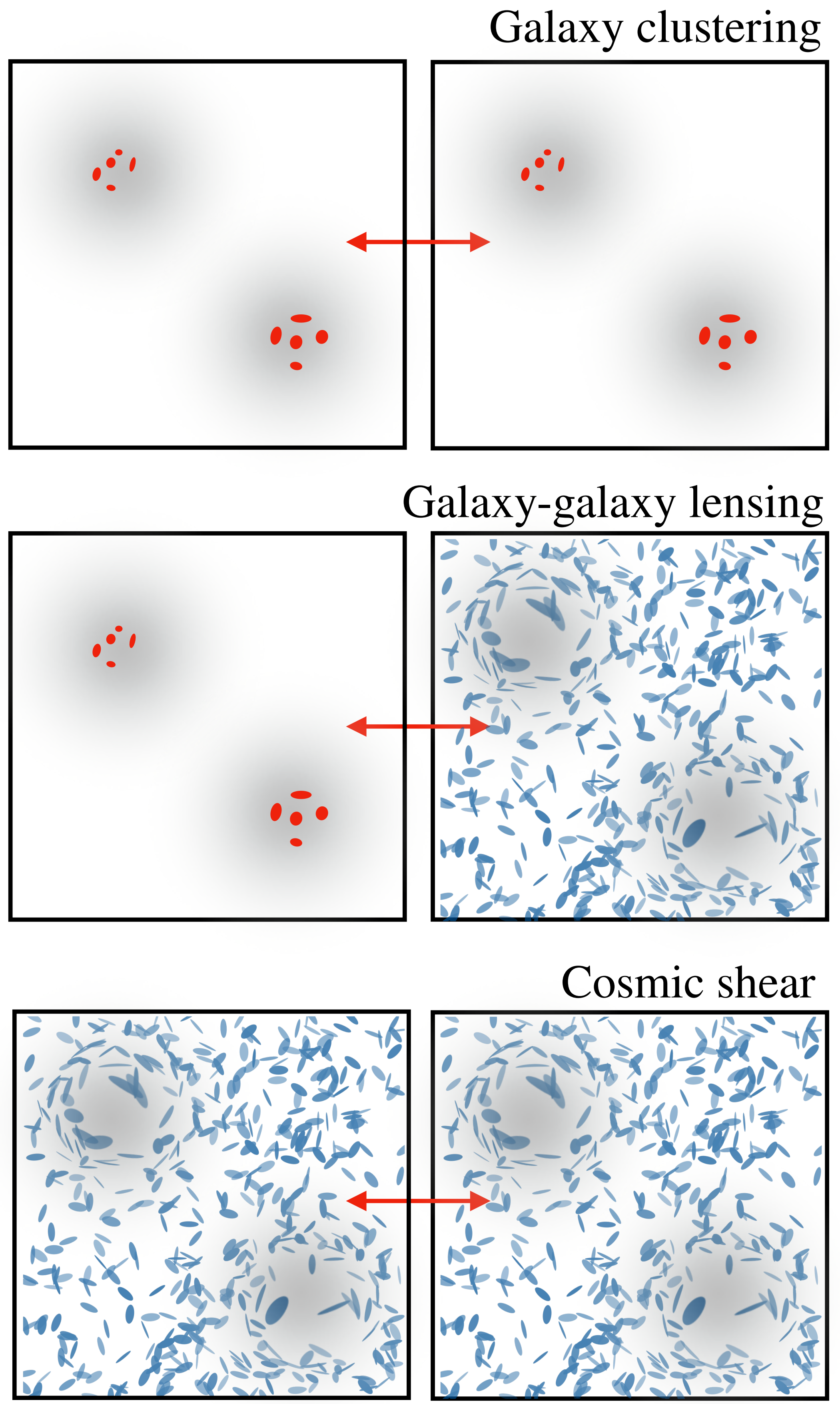
Work in collaboration with Eric Baxter (UHawaii), Chihway Chang (UChicago//KICP) and many others from SPT and DES collaborations

DARK ENERGY SURVEY

SOUTH POLE TELESCOPE

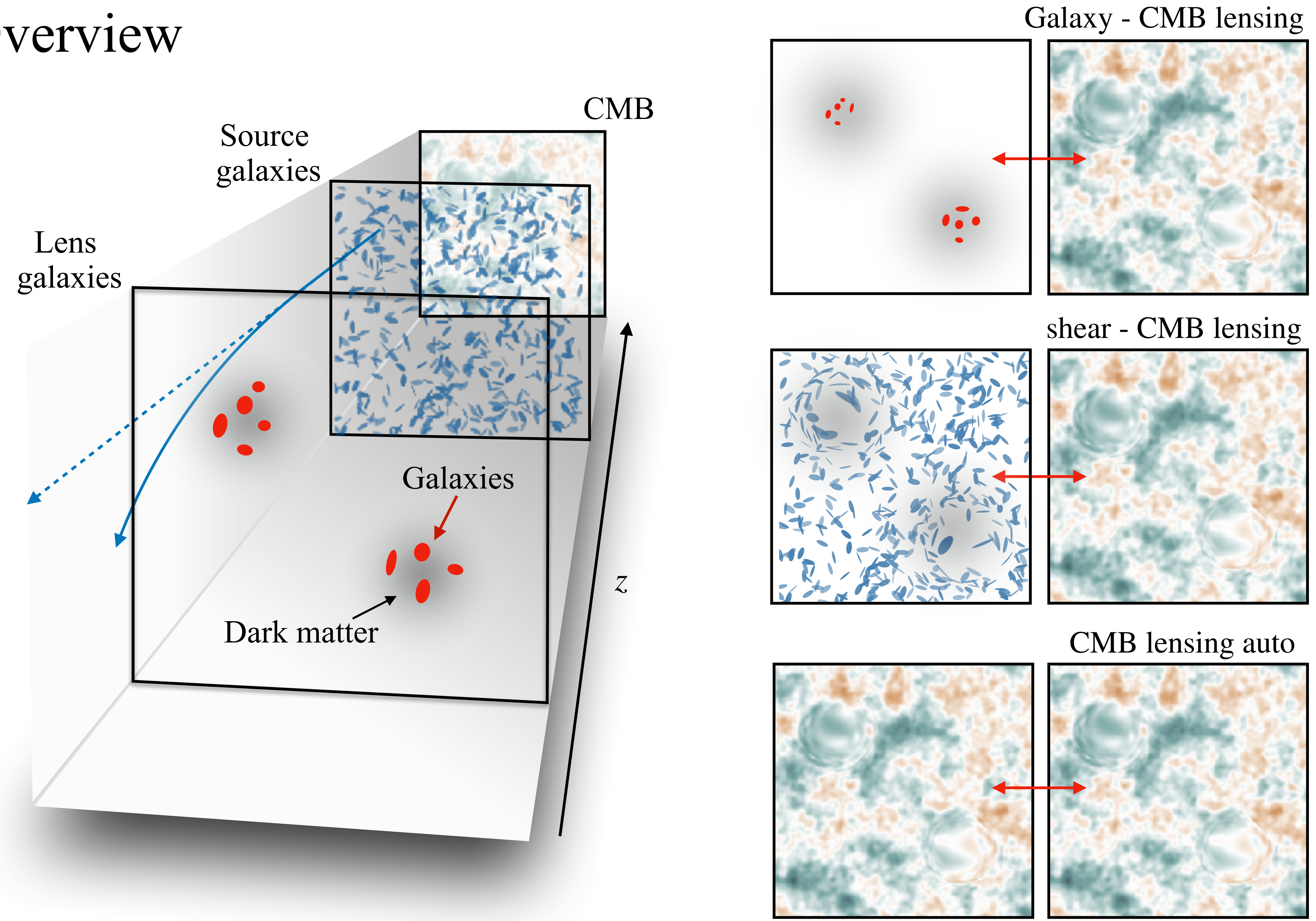
Overview





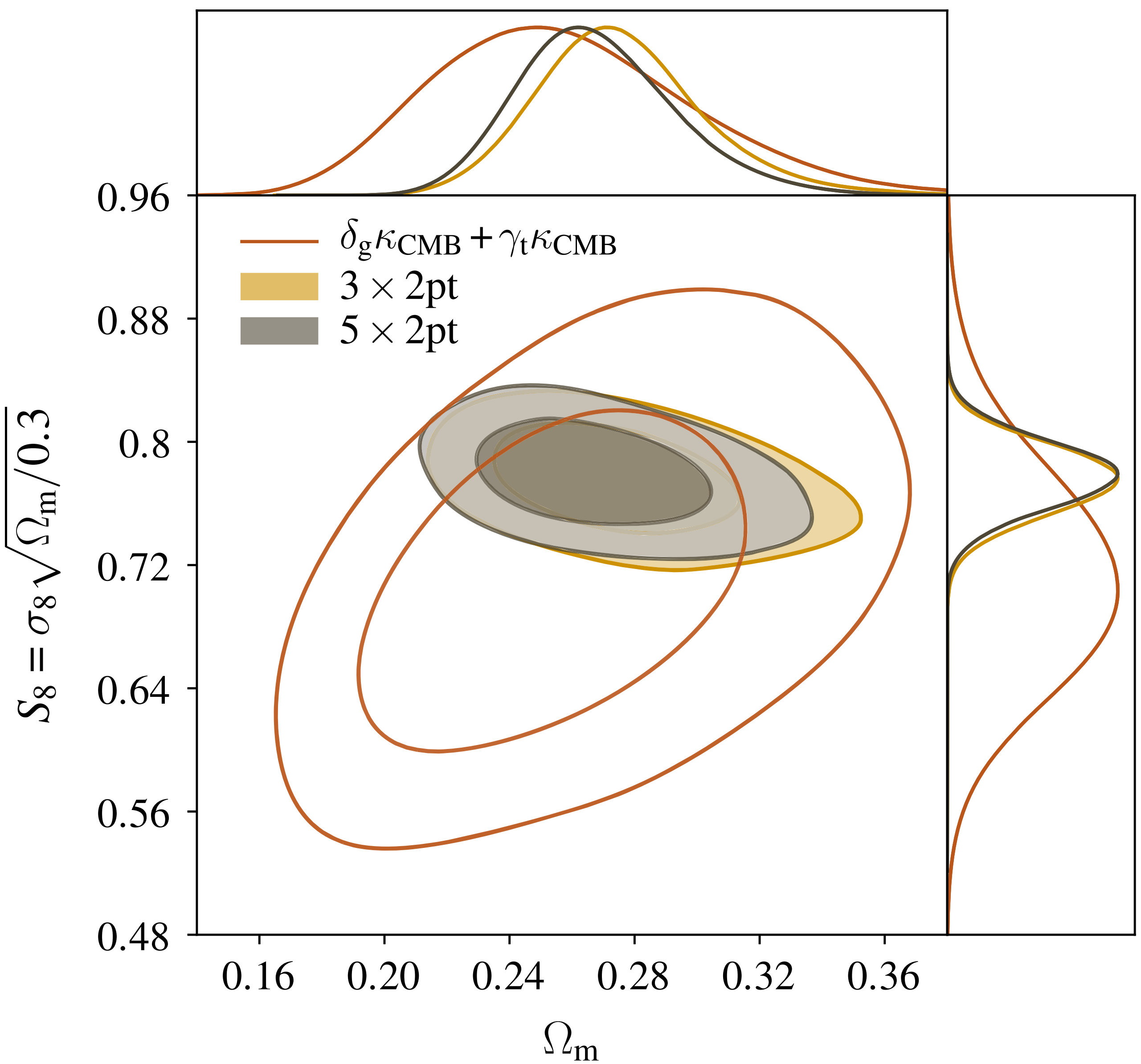
Three 2pt functions = “3x2pt”

Overview

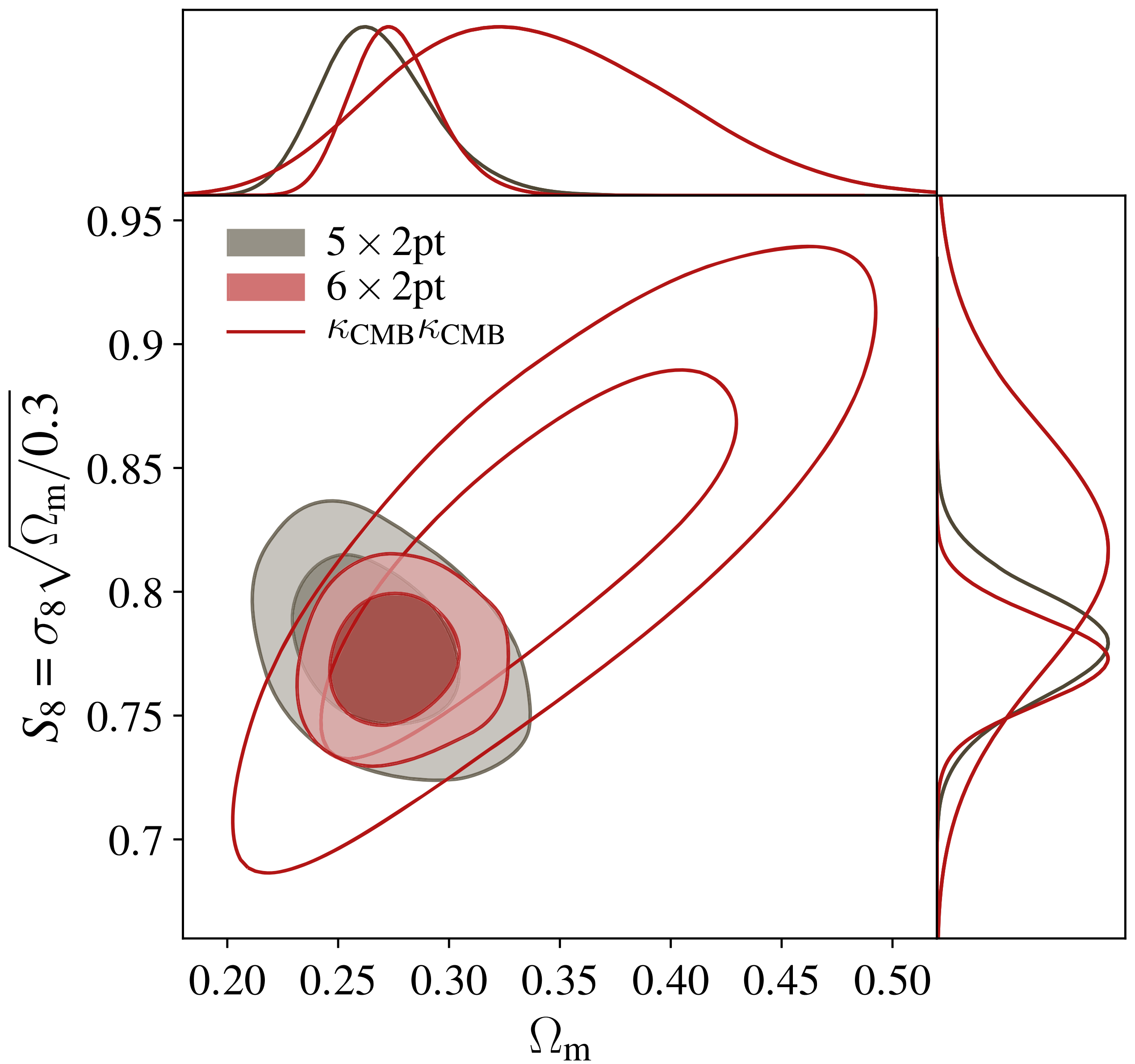


Six 2pt functions = “6x2pt”

Y1 results



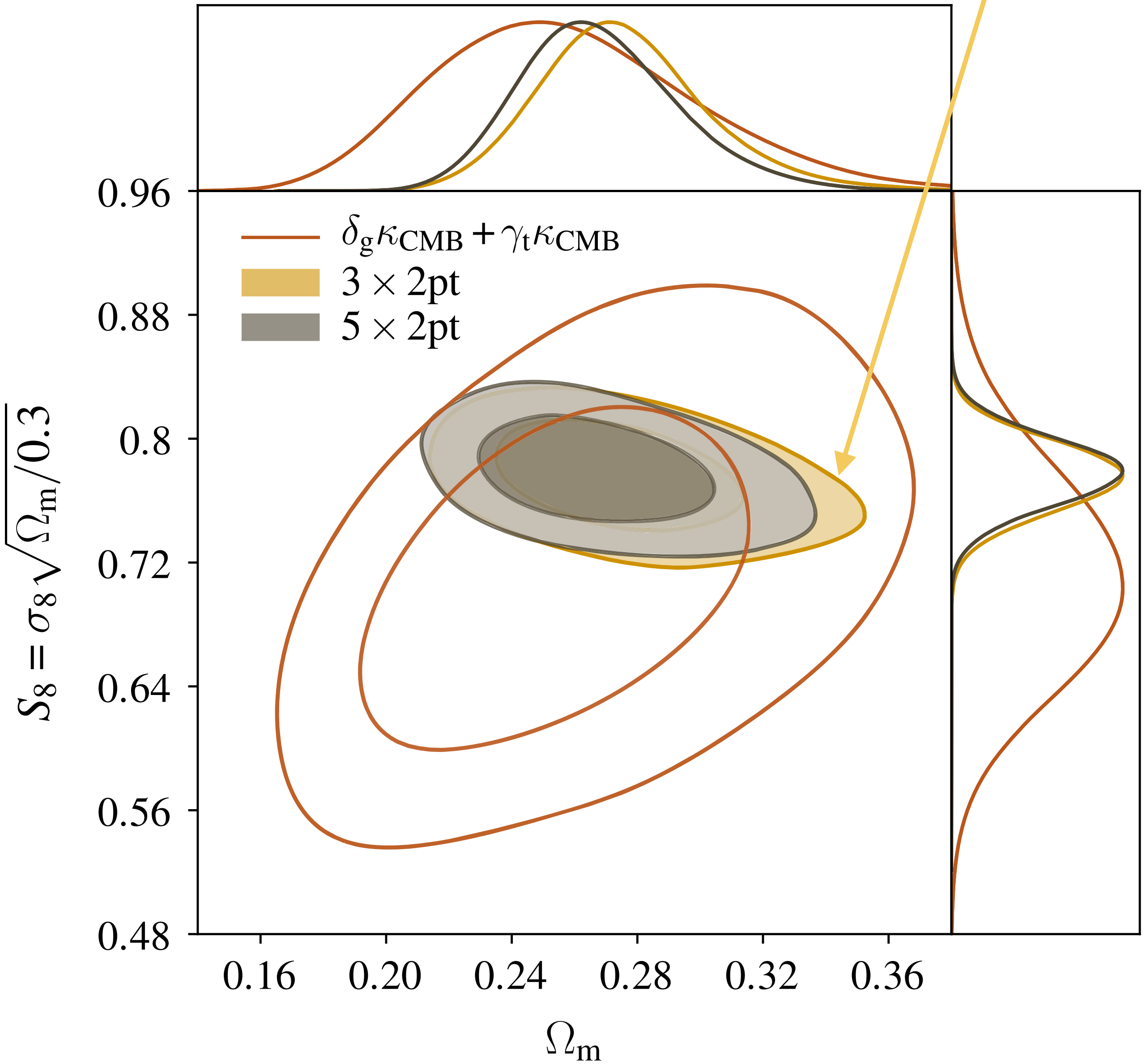
$\delta_g\kappa_{CMB} + \gamma_t\kappa_{CMB}$
3×2pt
5×2pt
0.96
0.88
0.8
0.72
0.64
0.56
0.48
$S_8 = \sigma_8\sqrt{\Omega_m/0.3}$
0.16
0.20
0.24
0.28
0.32
0.36
Ω_m

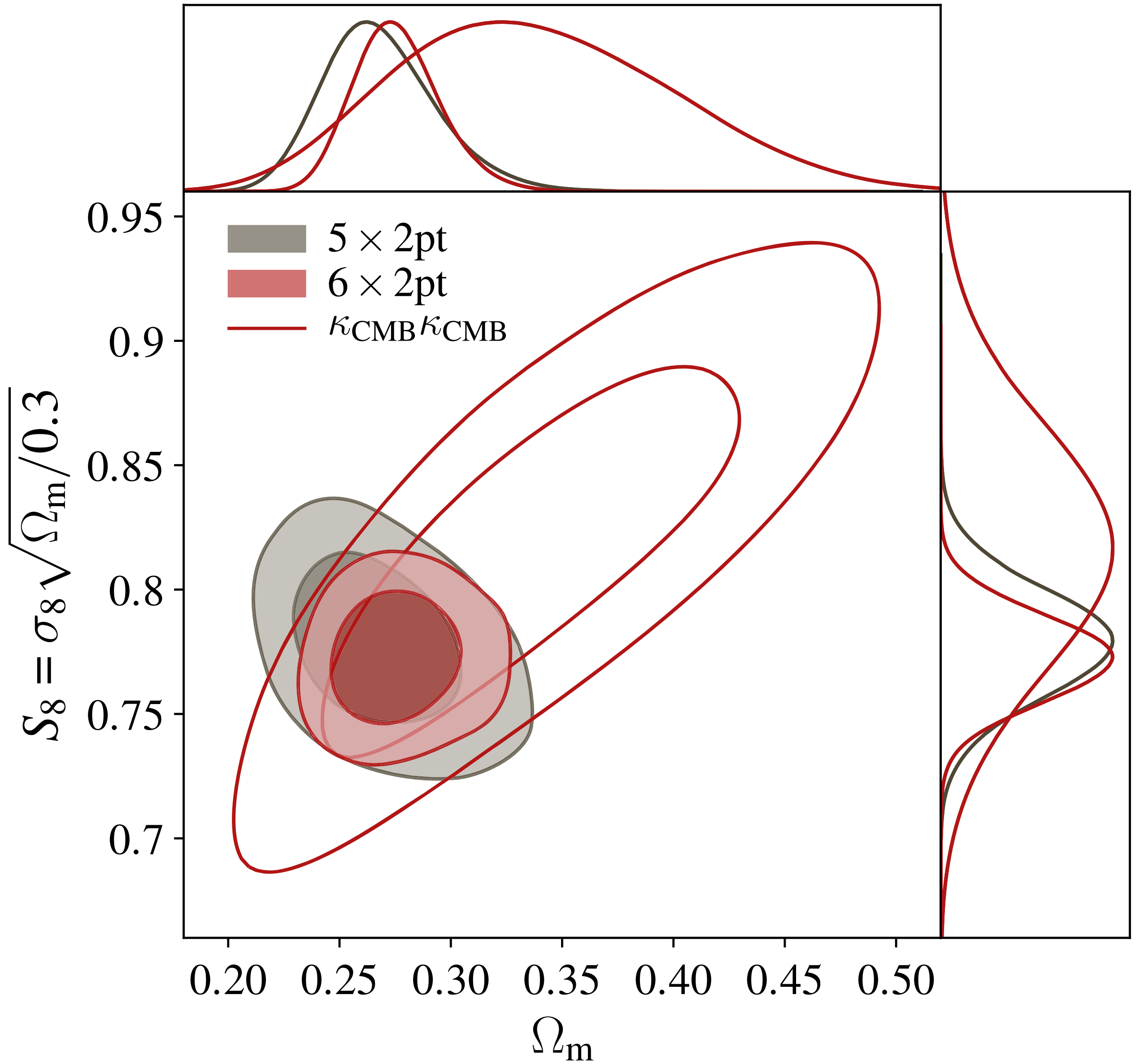


5×2pt
6×2pt
$\kappa_{CMB}\kappa_{CMB}$
0.95
0.9
0.85
0.8
0.75
0.7
$S_8 = \sigma_8\sqrt{\Omega_m/0.3}$
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Ω_m

Y1 results

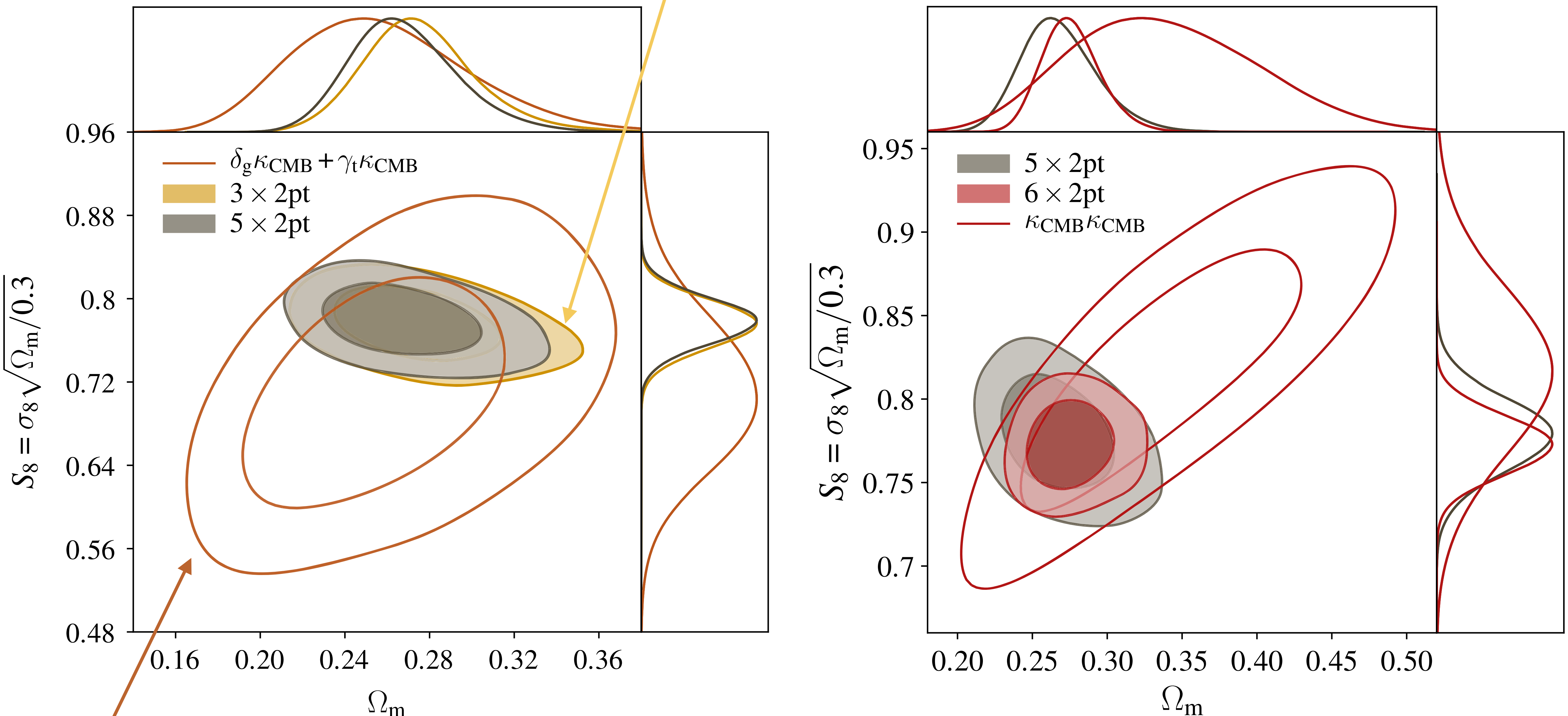
Constraints from DES alone (3x2pt)





Y1 results

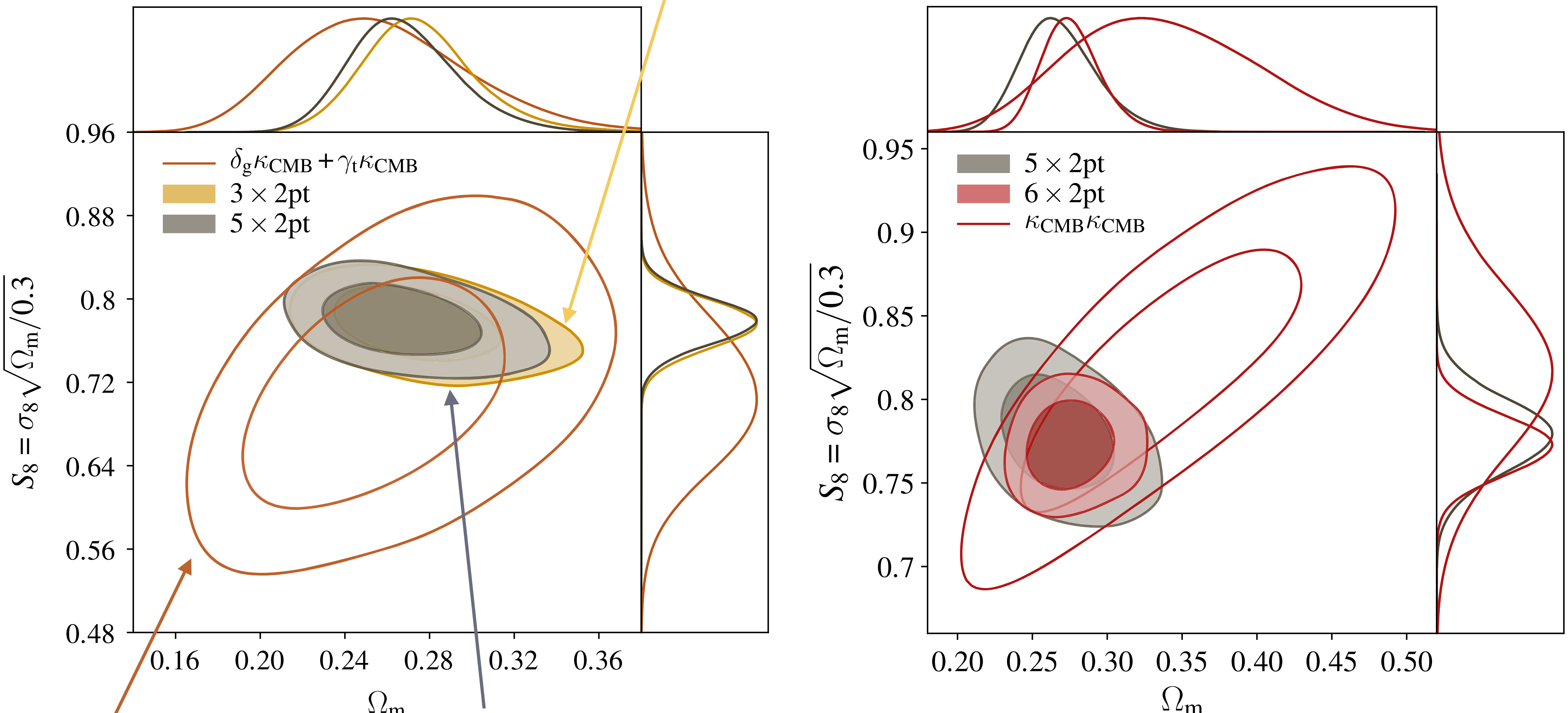
Constraints from DES alone (3x2pt)



Constraints from CMB lensing
cross-correlations (2x2pt)

Y1 results

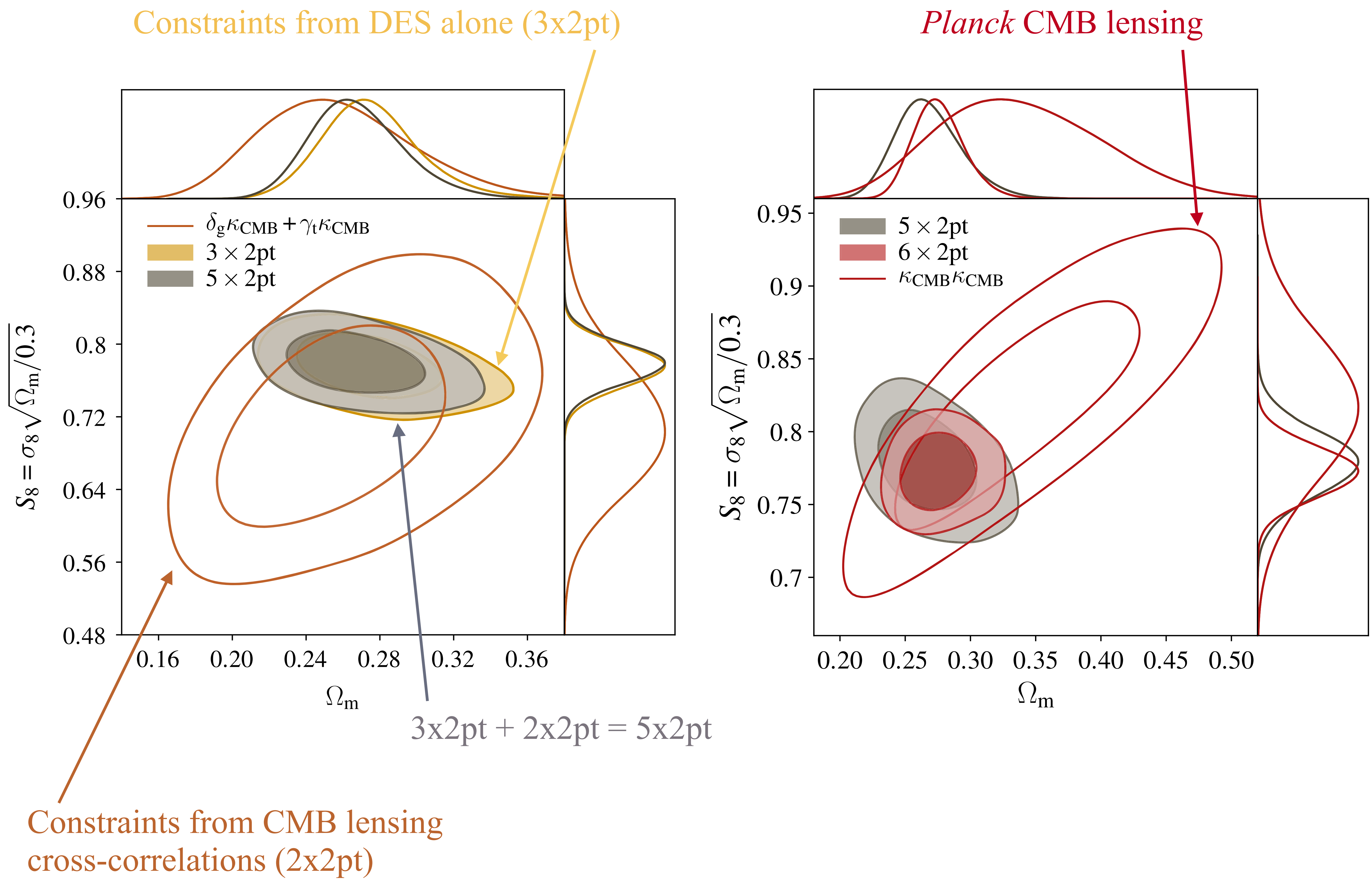
Constraints from DES alone (3x2pt)



3x2pt + 2x2pt = 5x2pt

Constraints from CMB lensing cross-correlations (2x2pt)

Y1 results

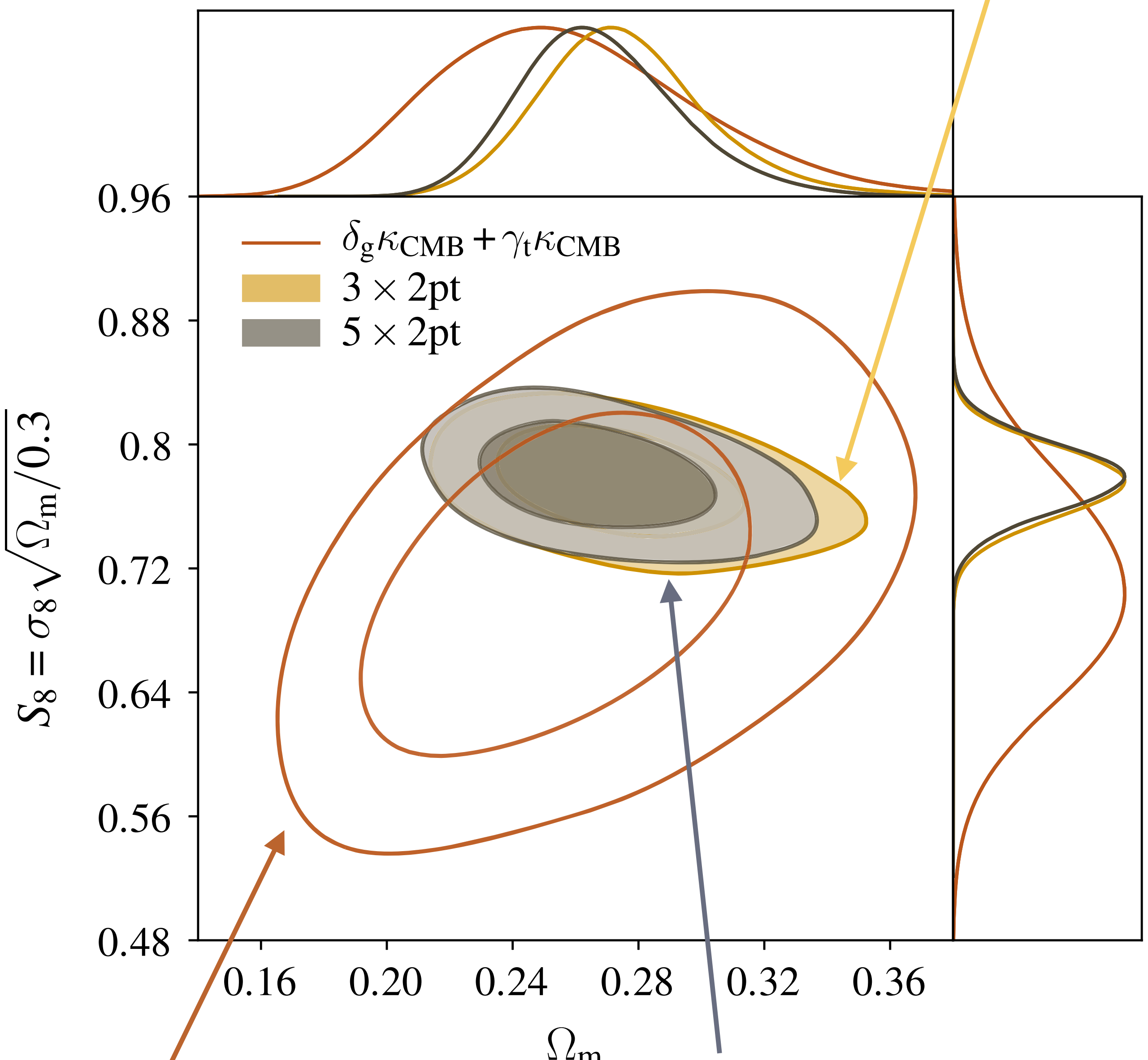


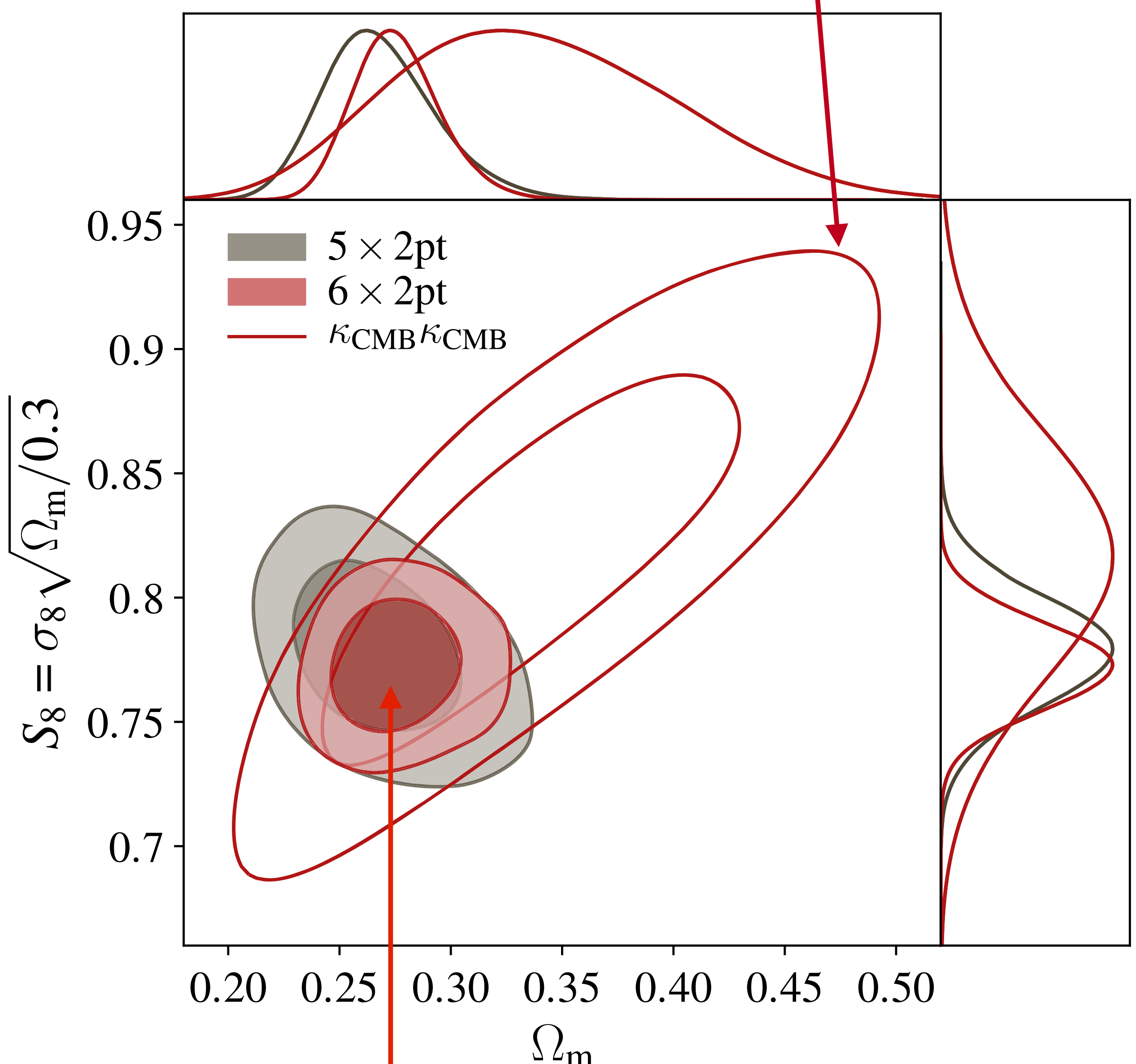
Constraints from DES alone (3x2pt)
Planck CMB lensing
$\delta_g\kappa_{CMB} + \gamma_t\kappa_{CMB}$
3×2pt
5×2pt
6×2pt
$\kappa_{CMB}\kappa_{CMB}$
$S_8 = \sigma_8\sqrt{\Omega_m/0.3}$
Ω_m
3x2pt + 2x2pt = 5x2pt
Constraints from CMB lensing cross-correlations (2x2pt)

Y1 results

Constraints from DES alone (3x2pt)

Planck CMB lensing



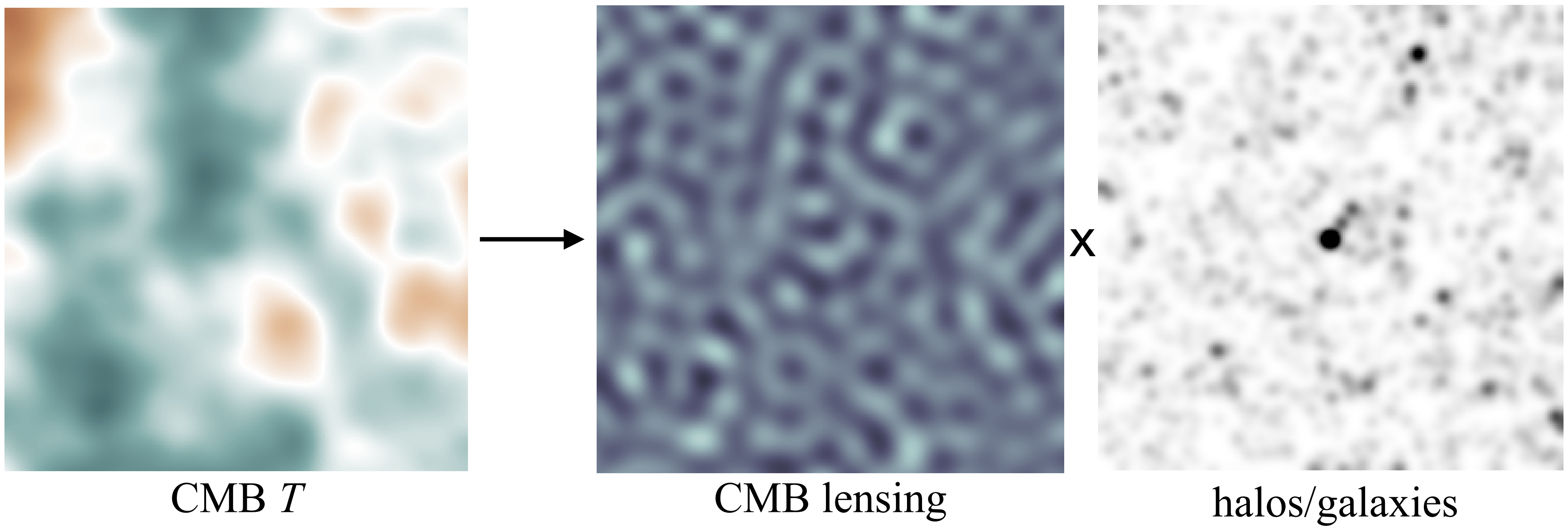


3x2pt + 2x2pt = 5x2pt

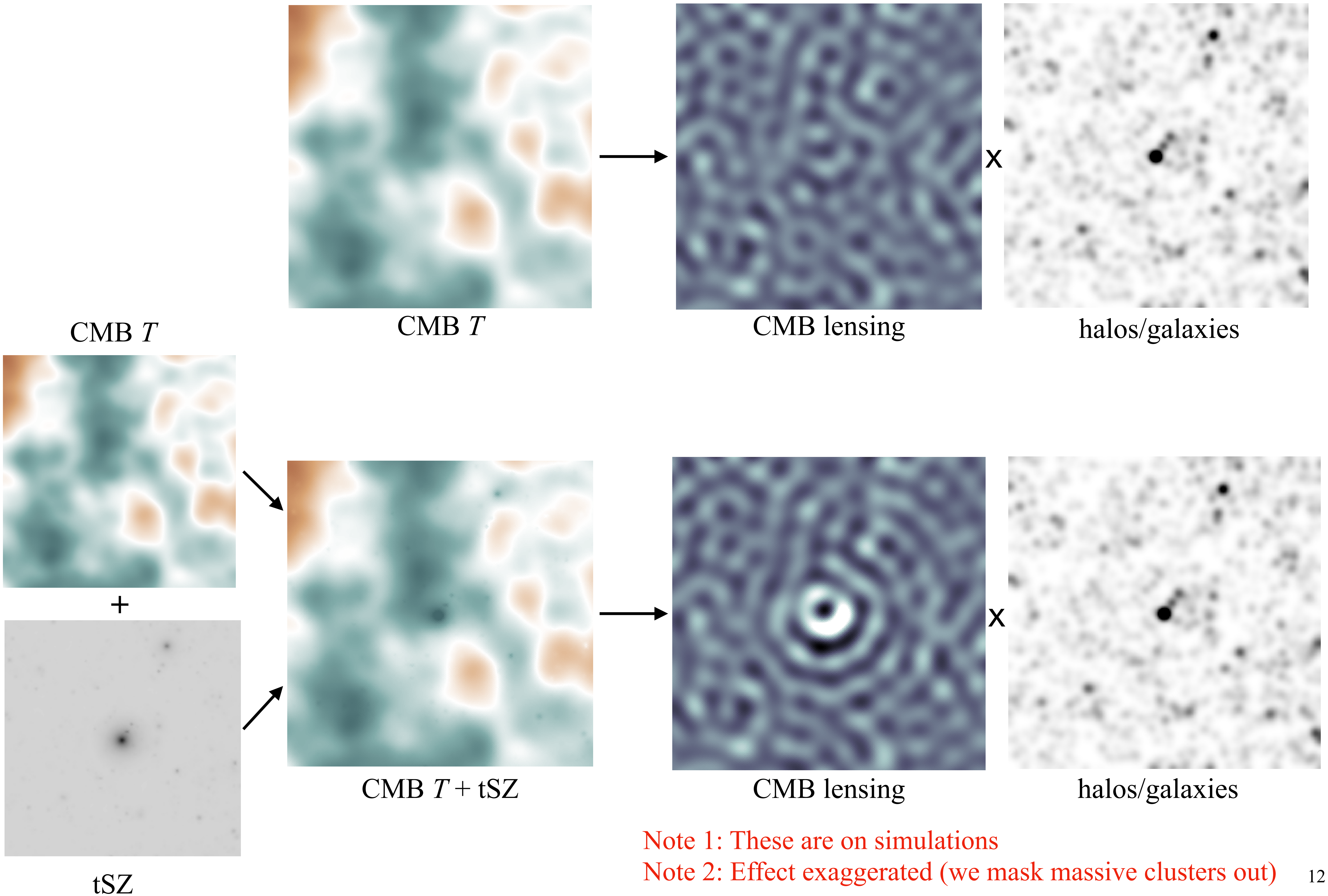
Constraints from CMB lensing
cross-correlations (2x2pt)

Final combined constraints (6x2pt)
~3% constraint on S_8

tSZ bias



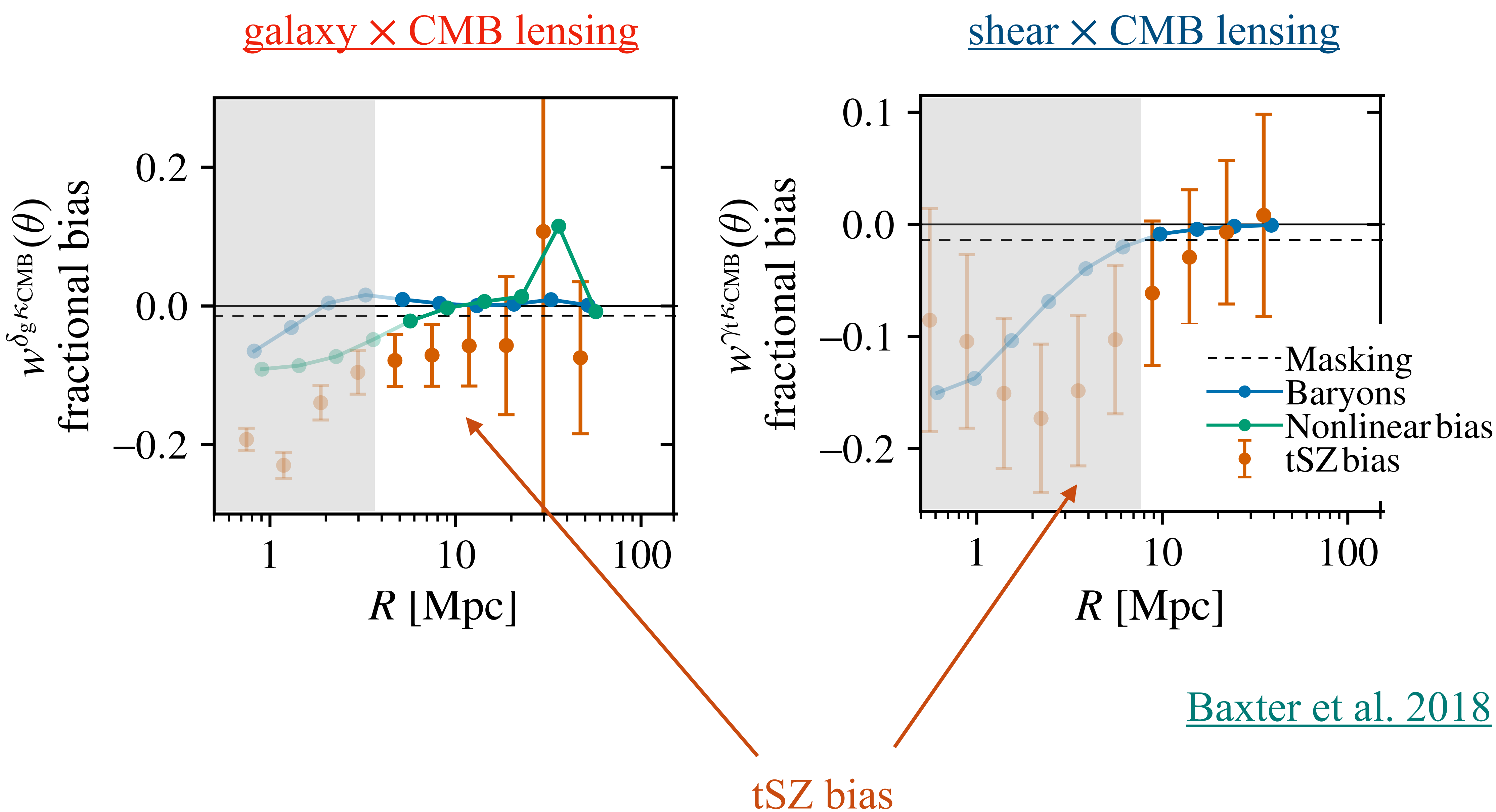
tSZ bias



Note 1: These are on simulations
Note 2: Effect exaggerated (we mask massive clusters out)

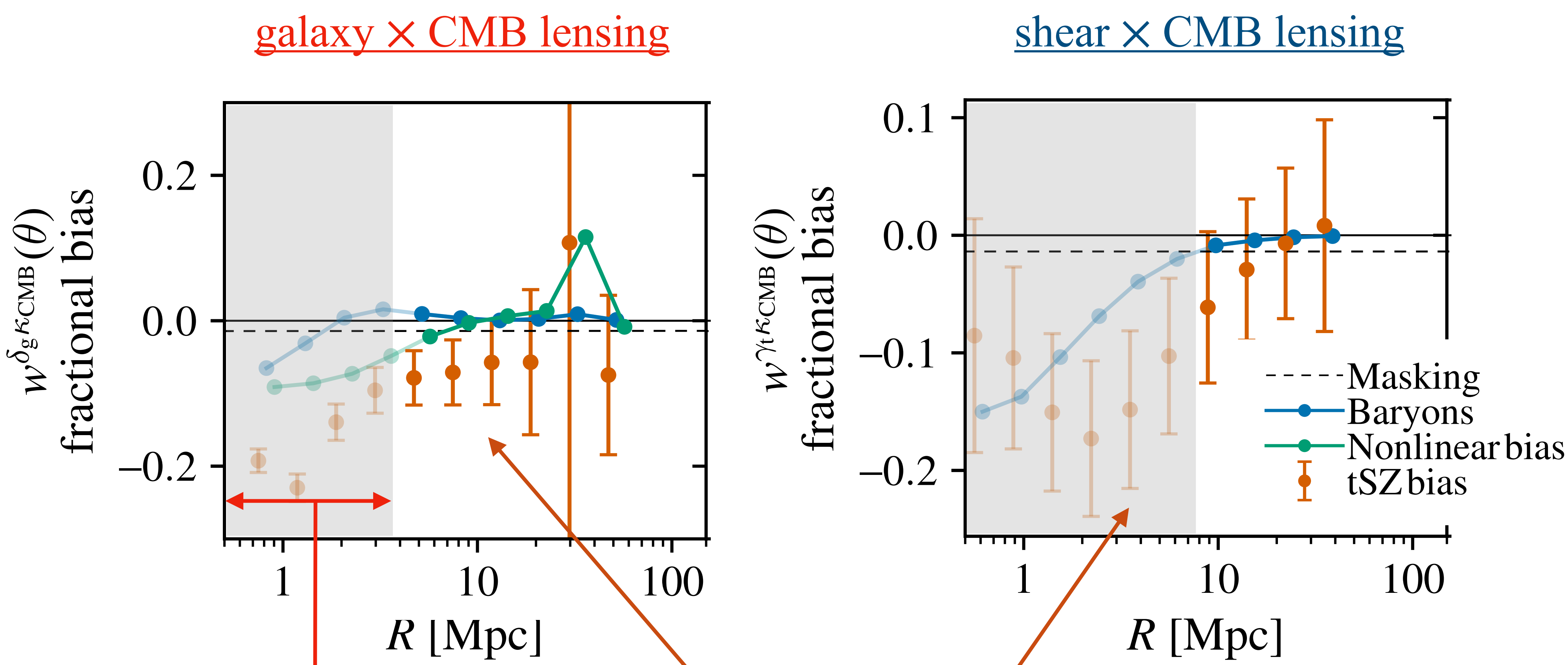
tSZ bias

tSZ bias was the main driver for our choice of angular scale cuts in DES-Y1 analysis



tSZ bias

tSZ bias was the main driver for our choice of angular scale cuts in DES-Y1 analysis

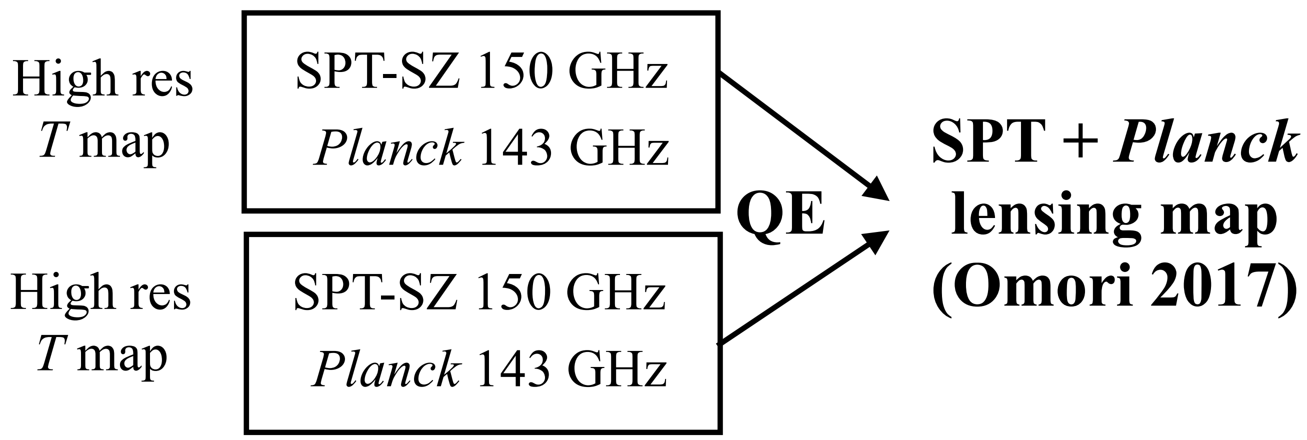


Baxter et al. 2018

Scales removed in the analysis

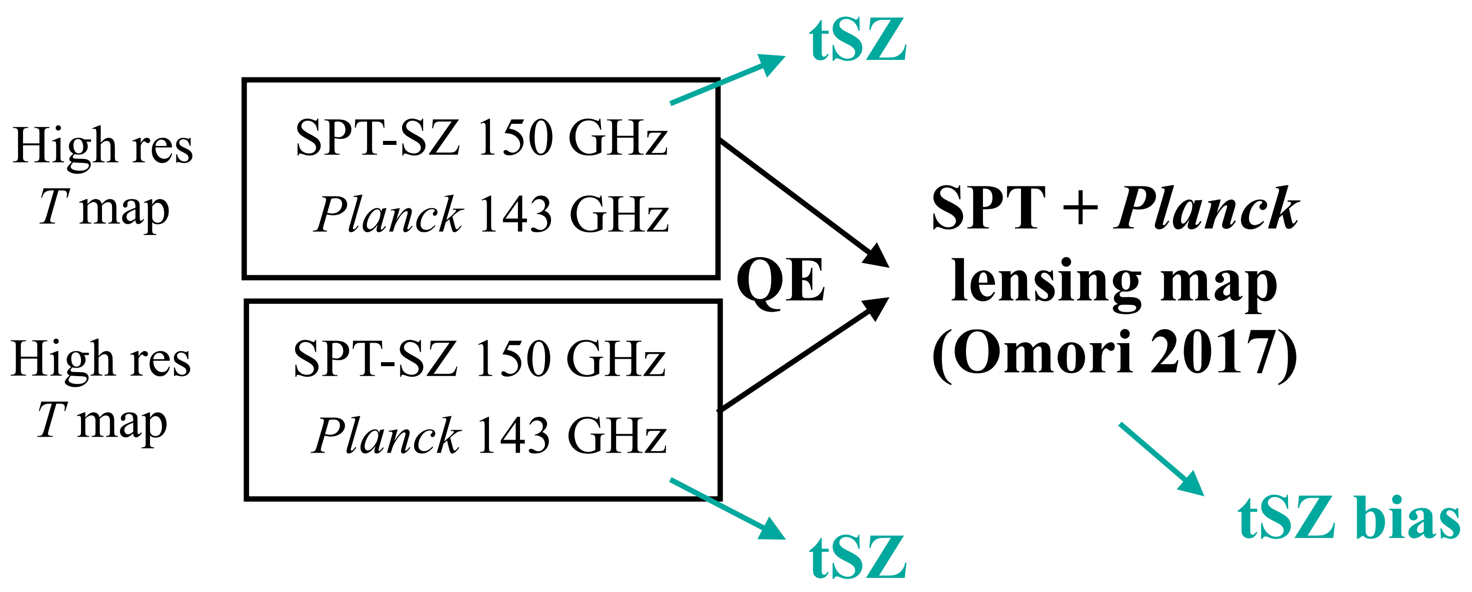
tSZ bias

Y3 improvement I:
tSZ-nulled lensing map



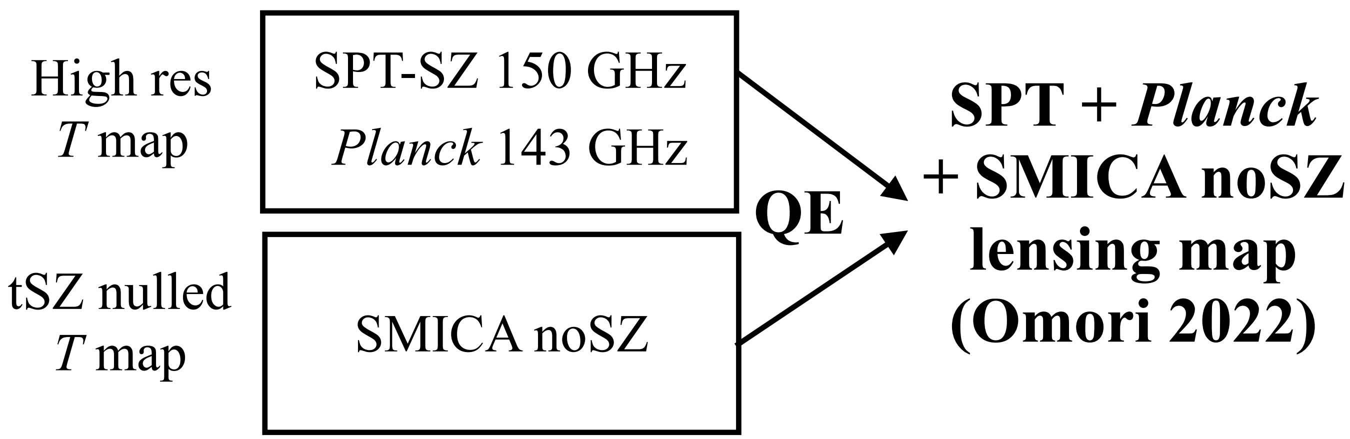
Omori et al. 2022

Y3 improvement I:
tSZ-nulled lensing map

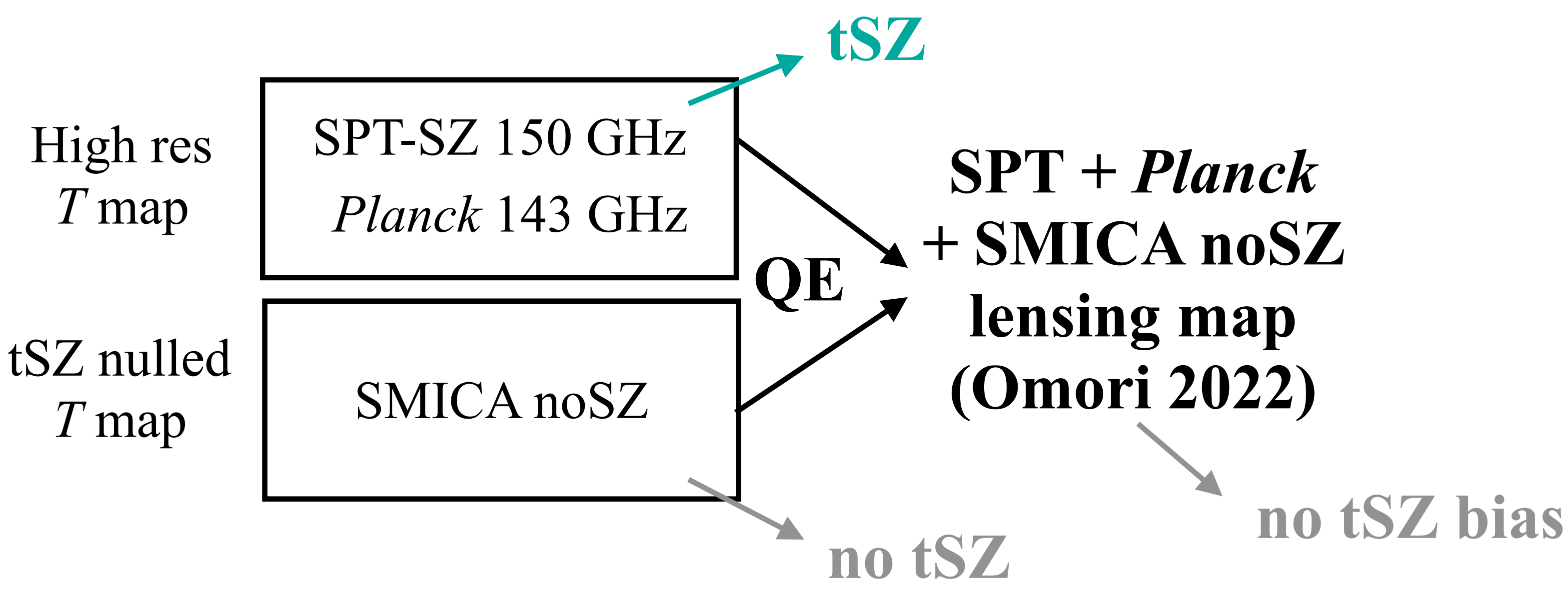


Omori et al. 2022

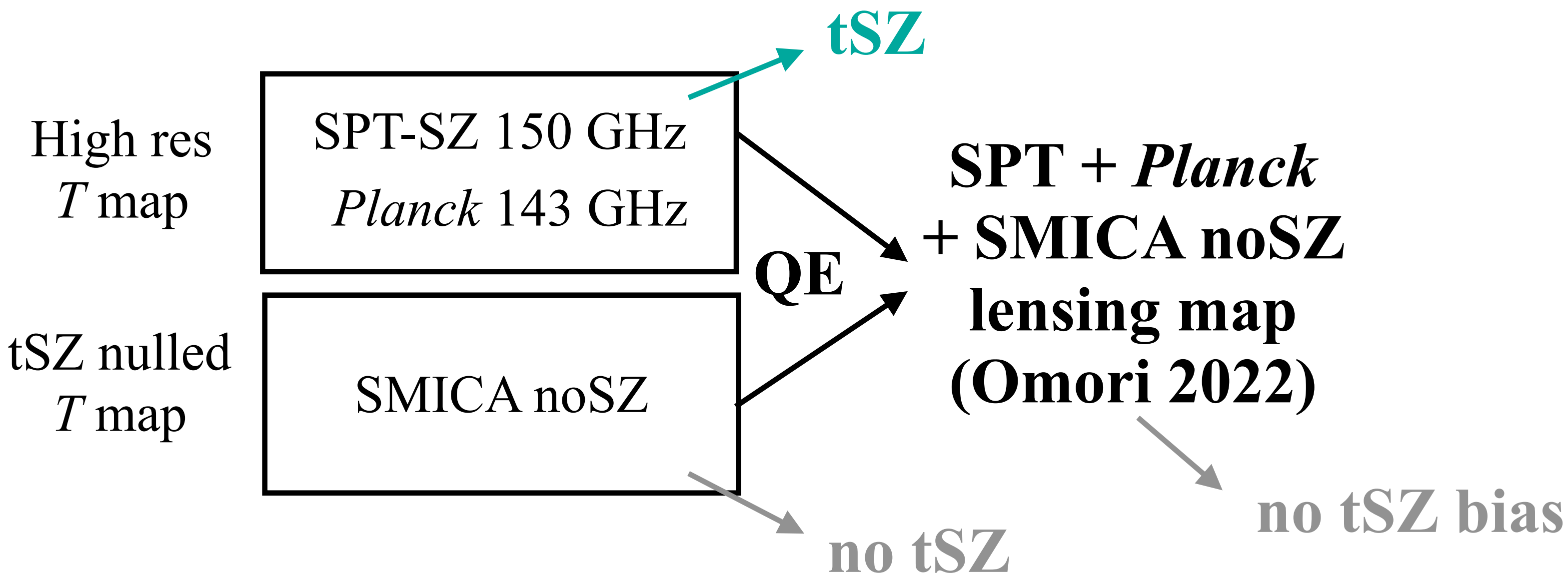
Y3 improvement I: tSZ-nulled lensing map

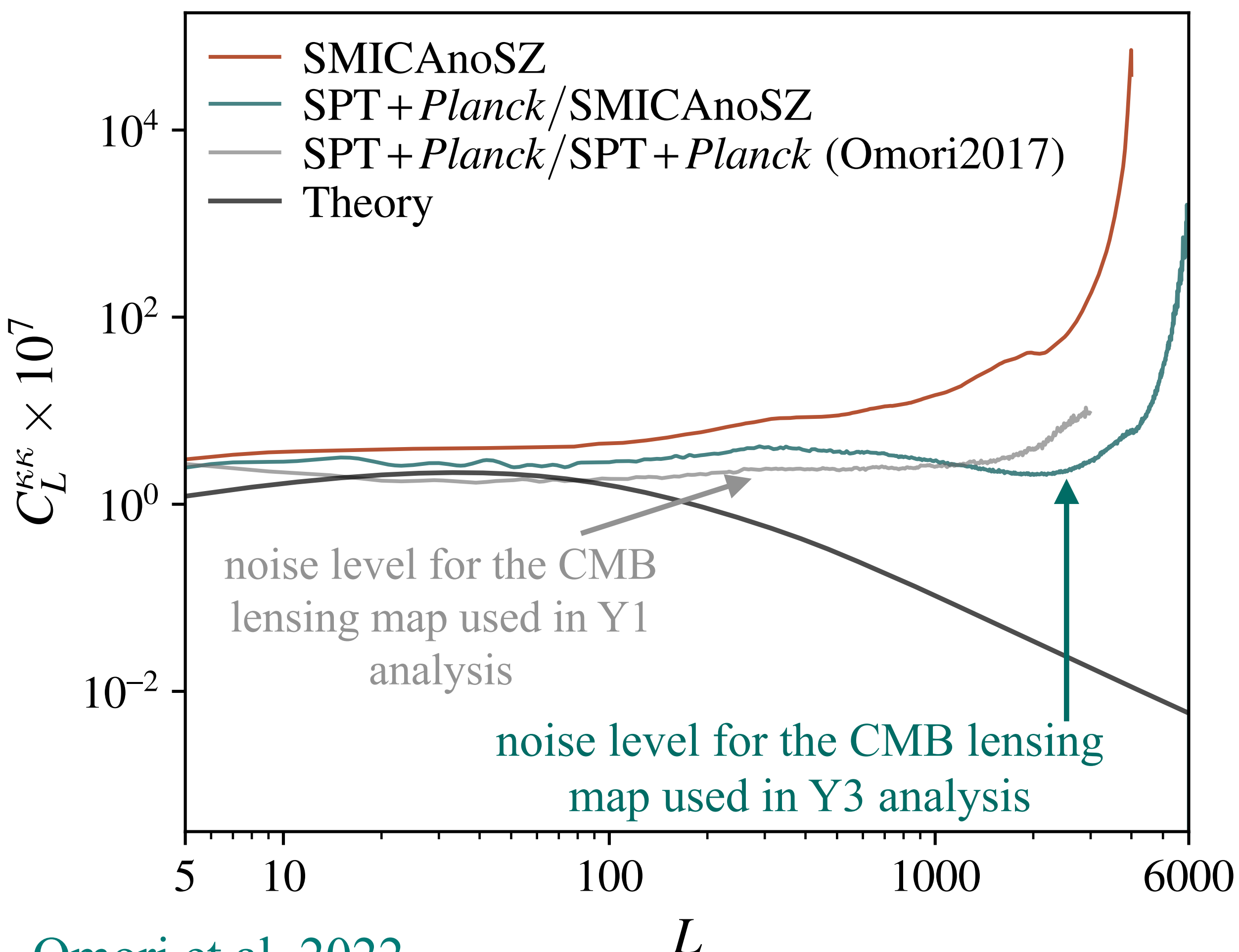


Y3 improvement I: tSZ-nulled lensing map



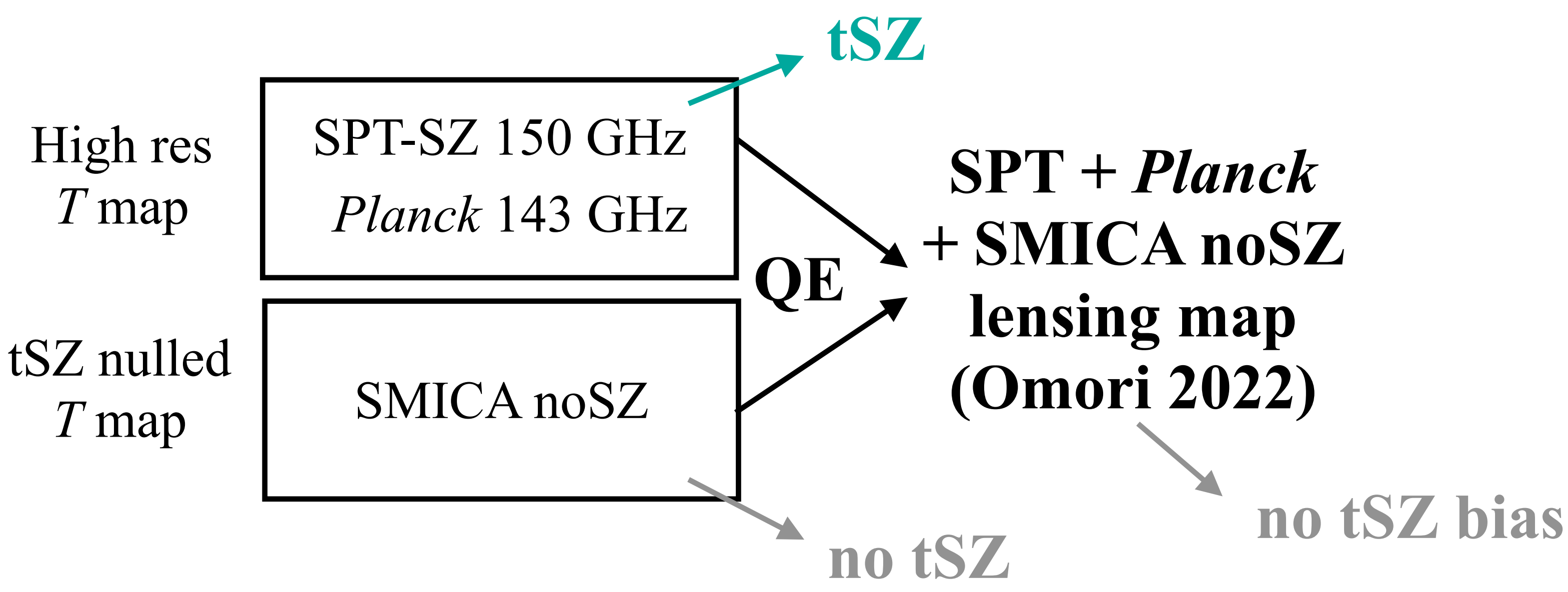
Y3 improvement I:
tSZ-nulled lensing map

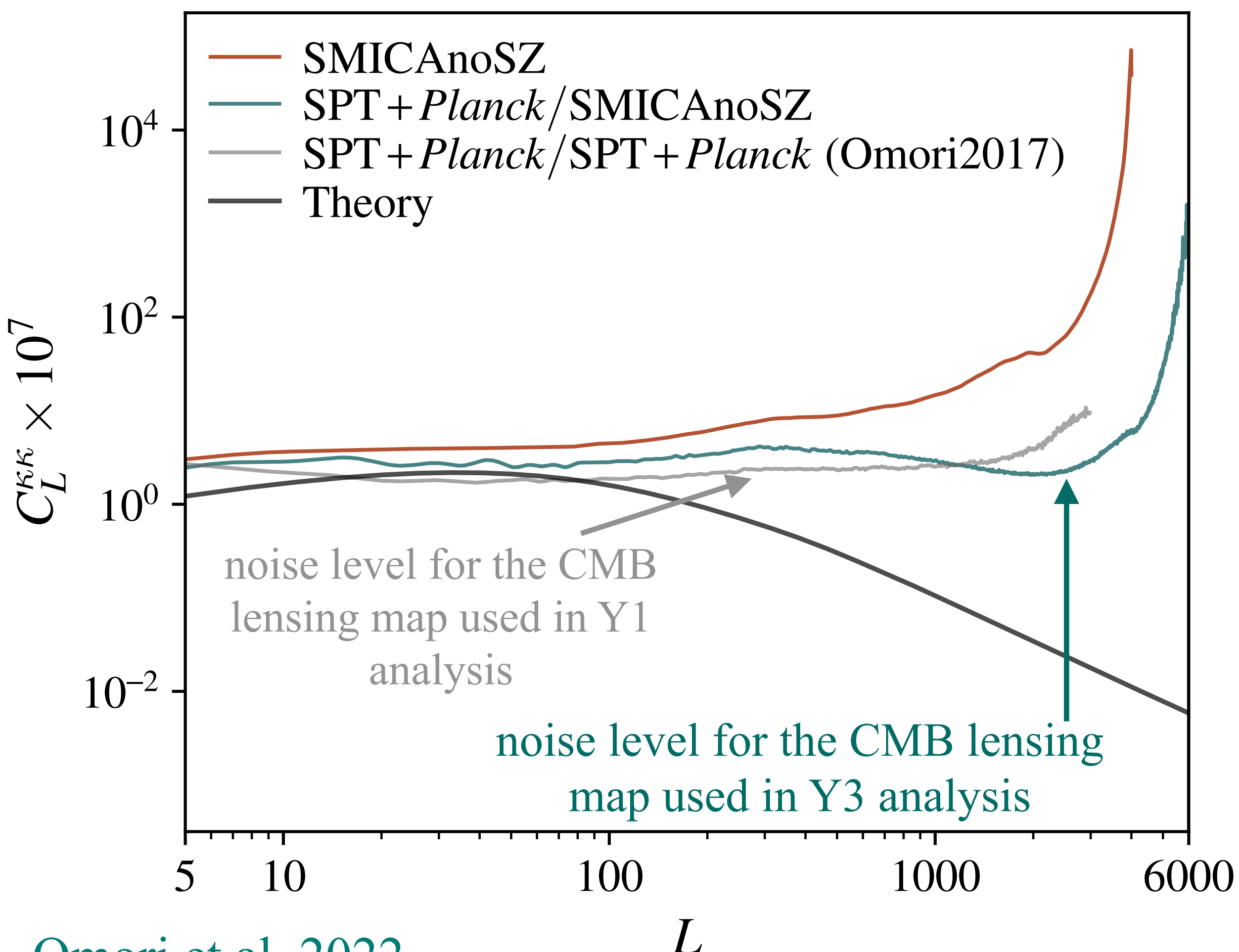




Omori et al. 2022

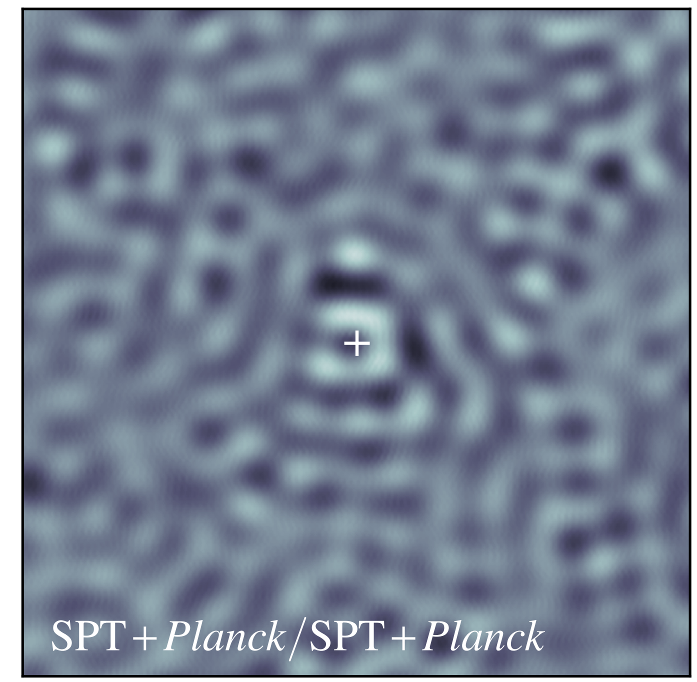
Y3 improvement I: tSZ-nulled lensing map



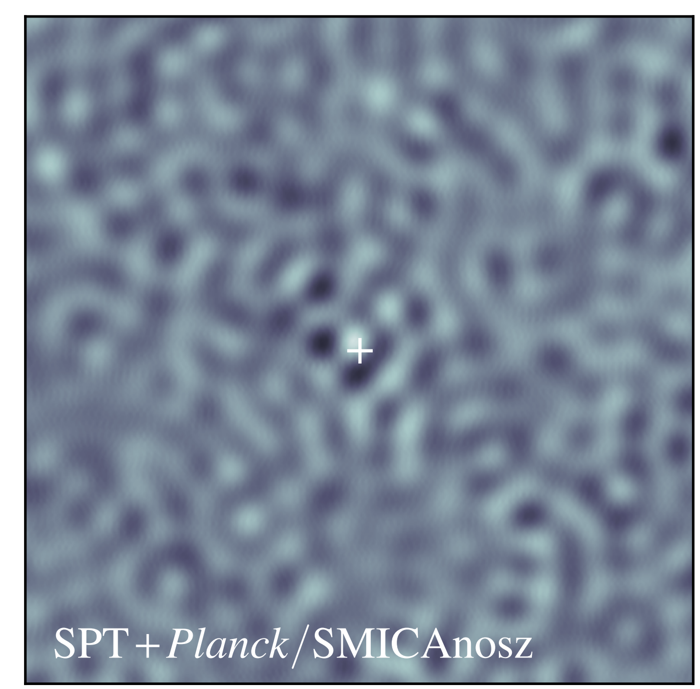


Omori et al. 2022

CMB lensing maps stacked at the location of clusters



Similar to the CMB lensing map used in Y1

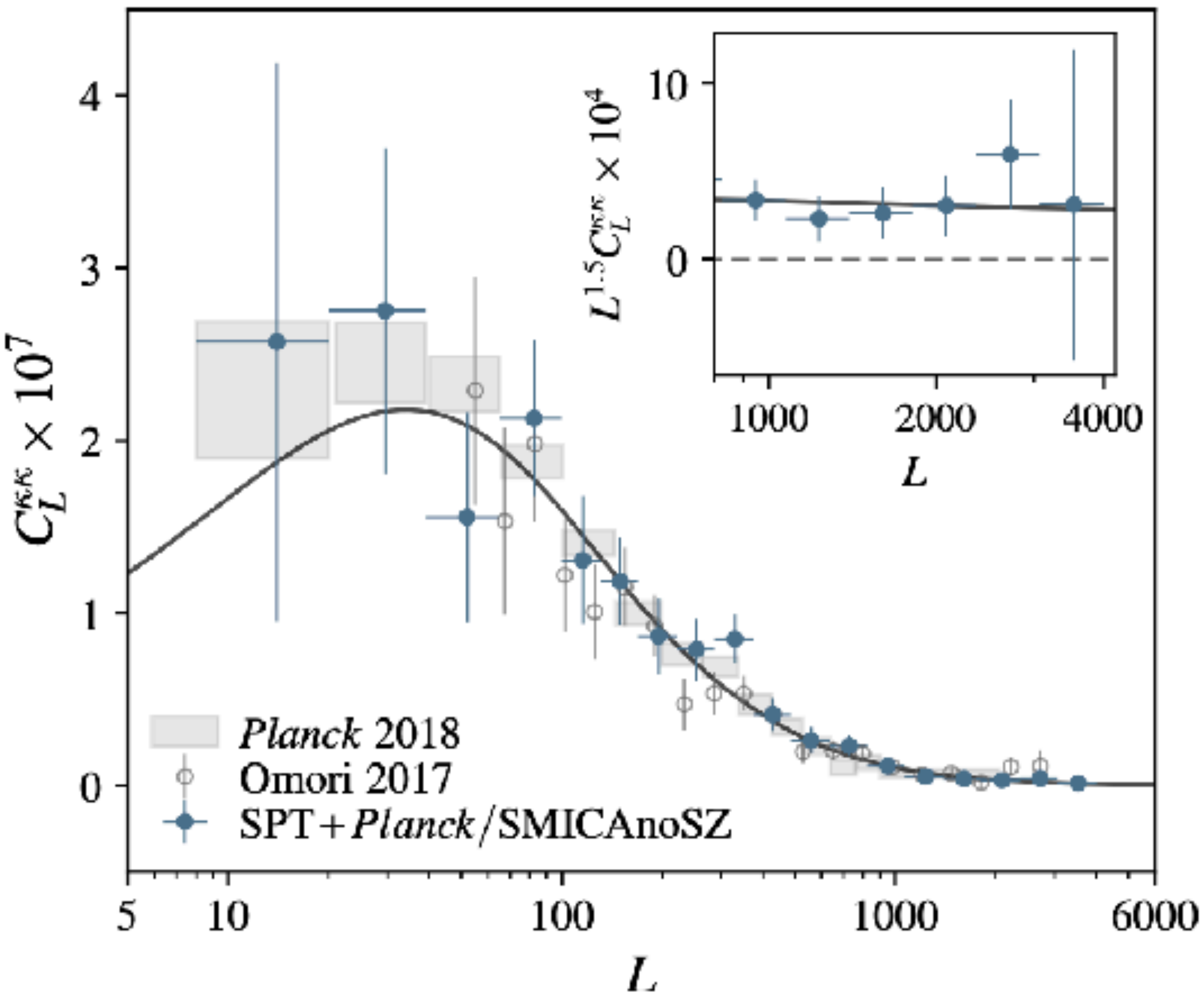


New CMB lensing map used in Y3

Omori et al. 2022

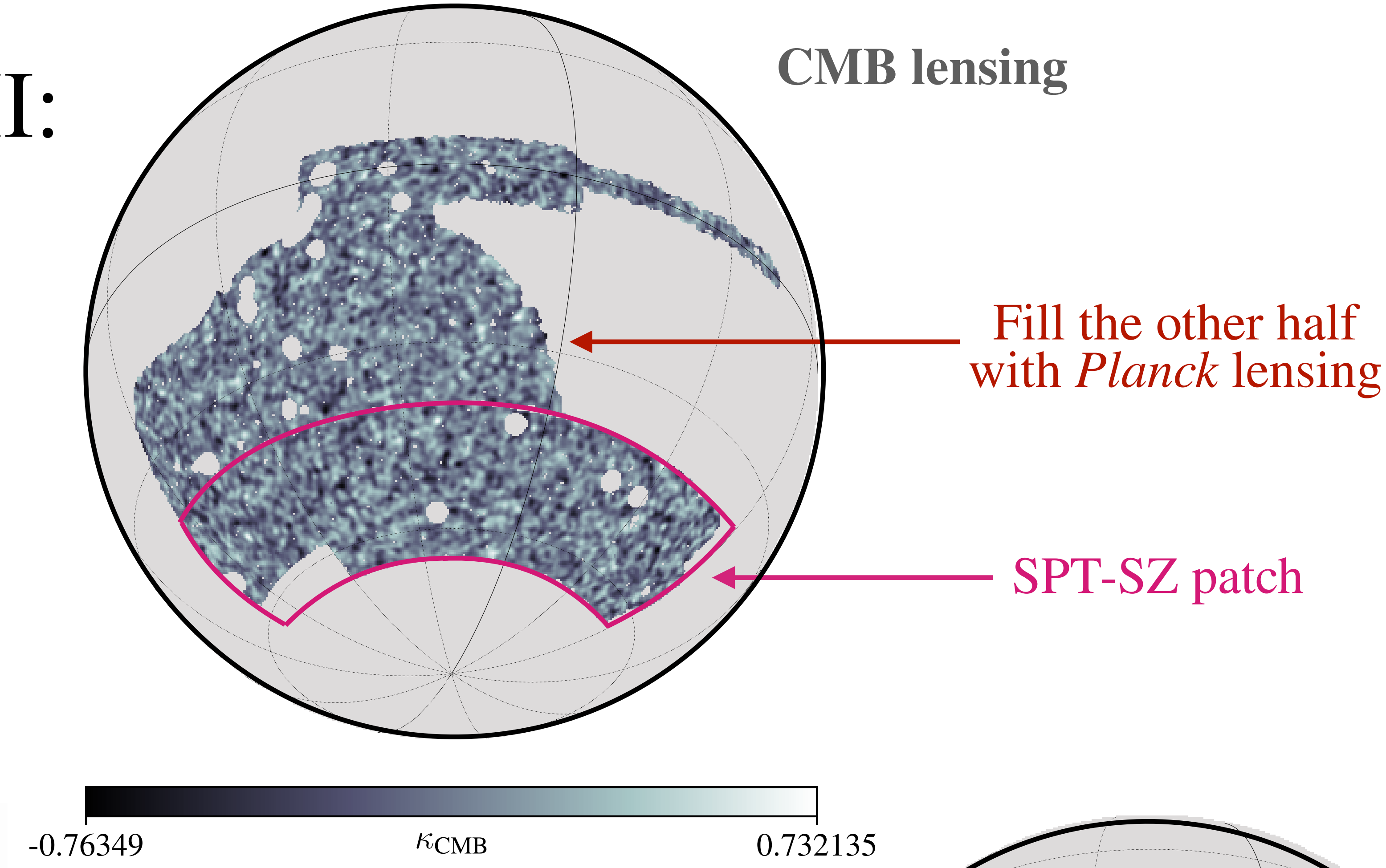
Y3 improvement I:
tSZ-nulled lensing map

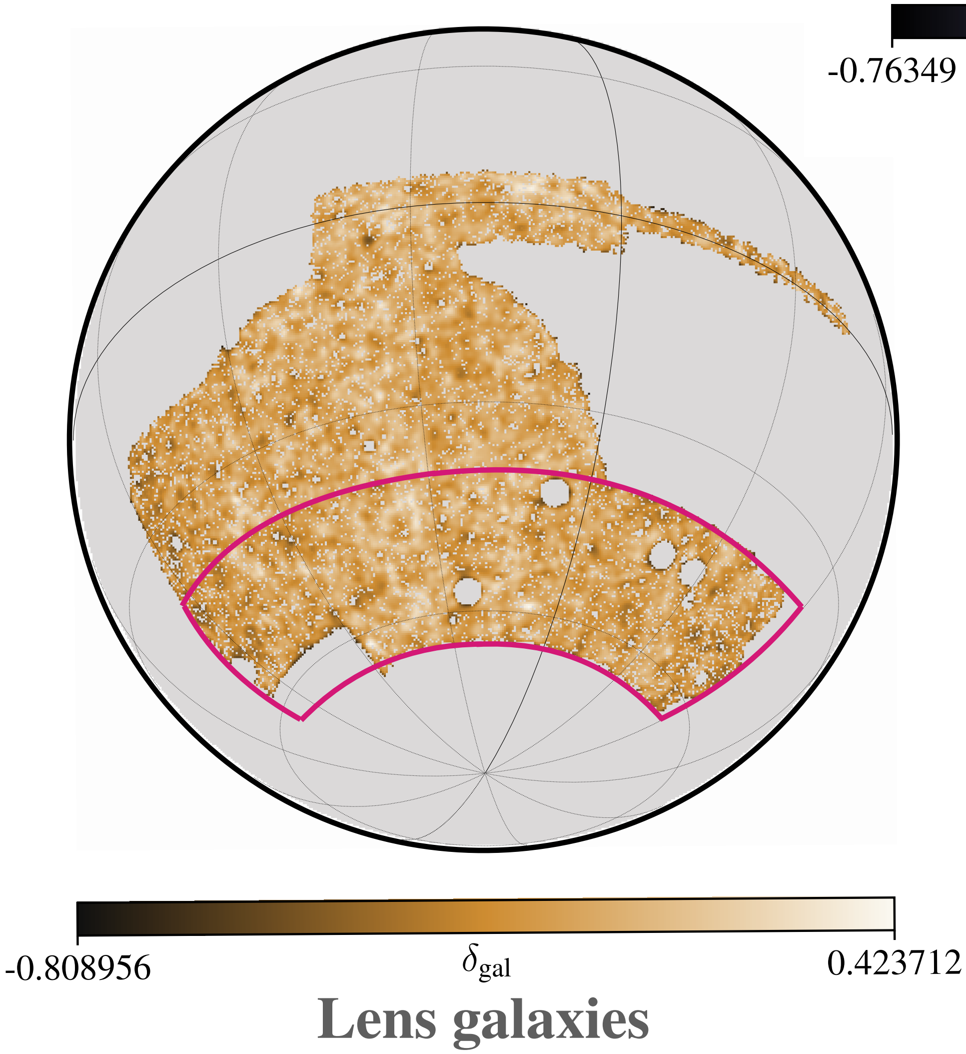
Omori et al. 2022

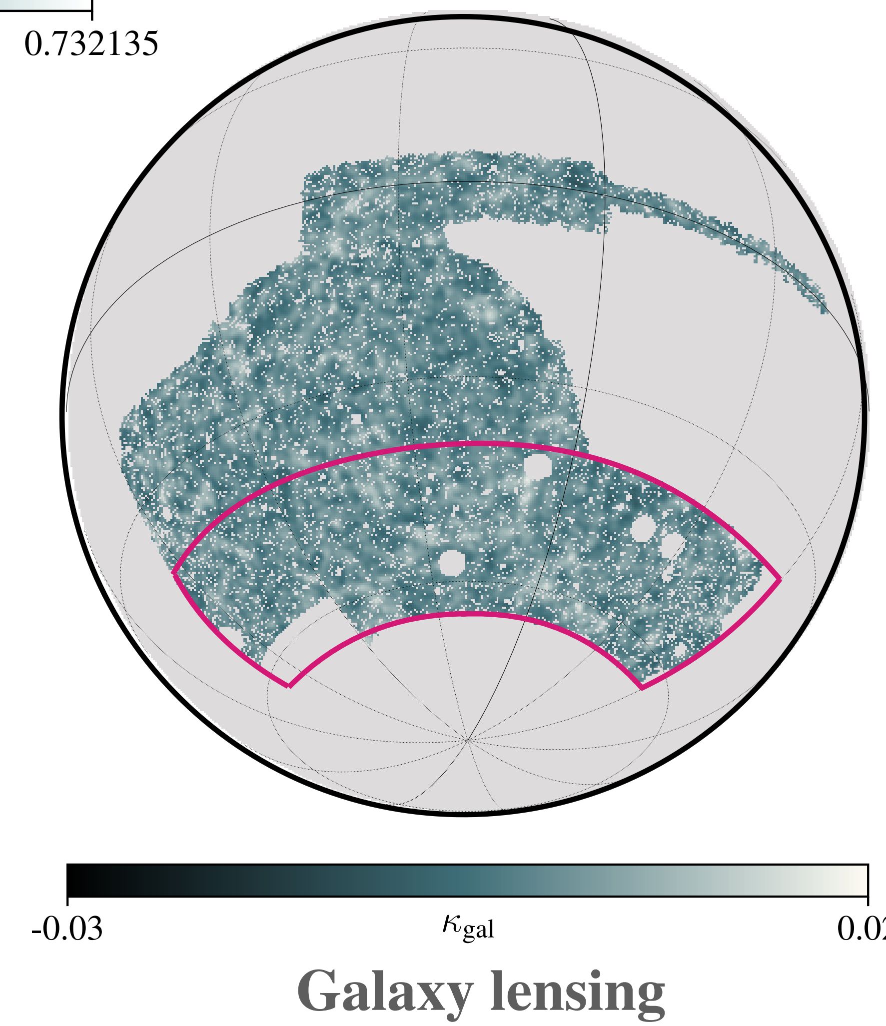


CMB lensing auto-spectrum

Y3 improvement II: Larger Y3 area

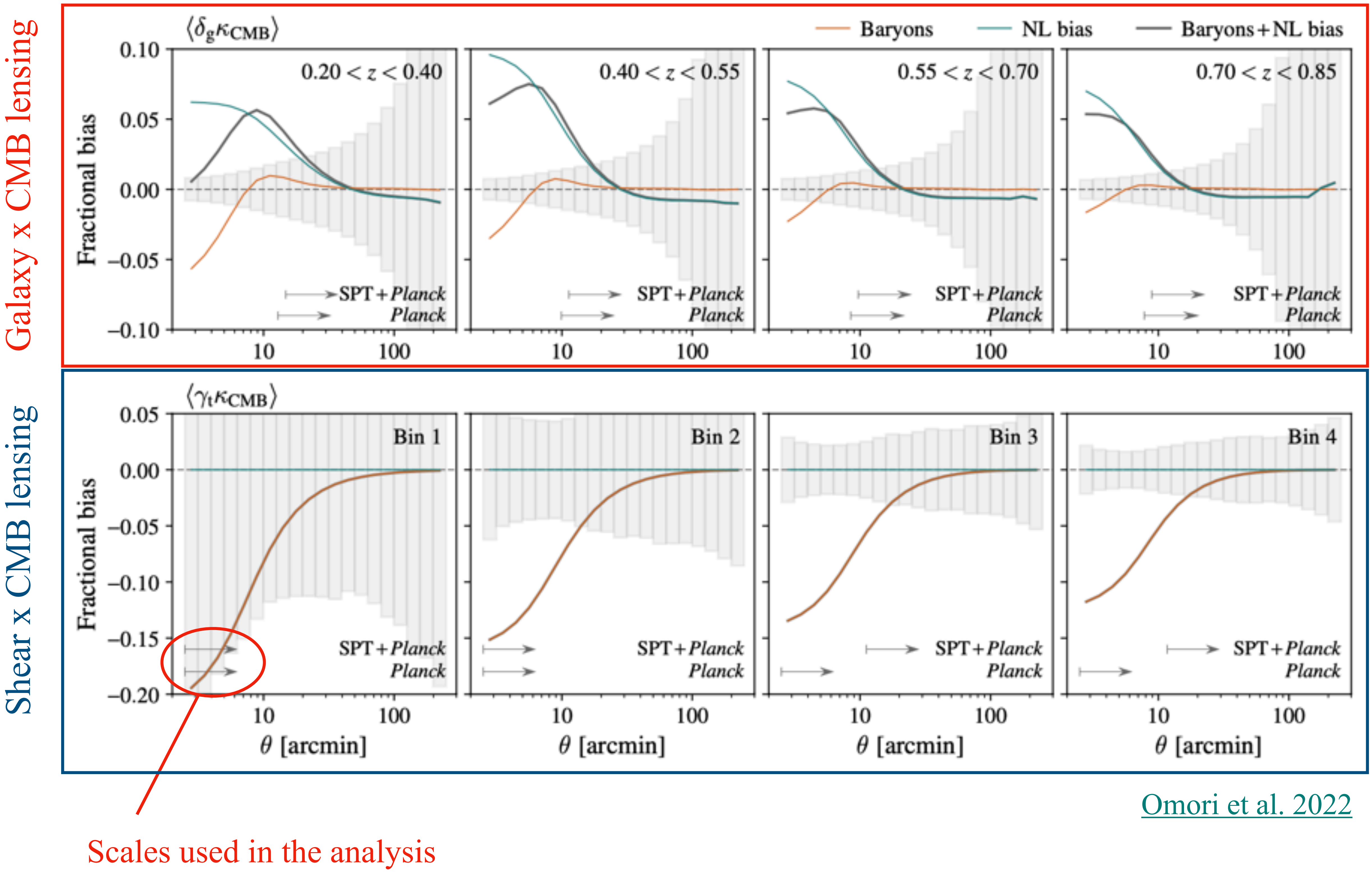






Scale cuts

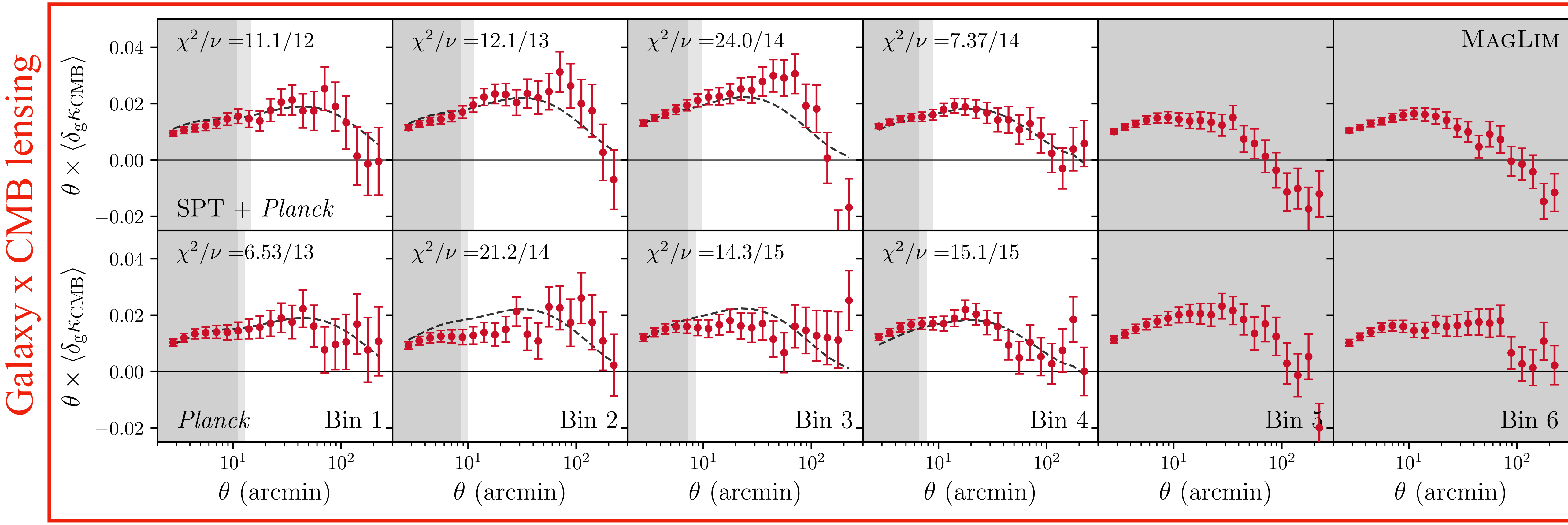
**Errors scaled down by a factor of 10

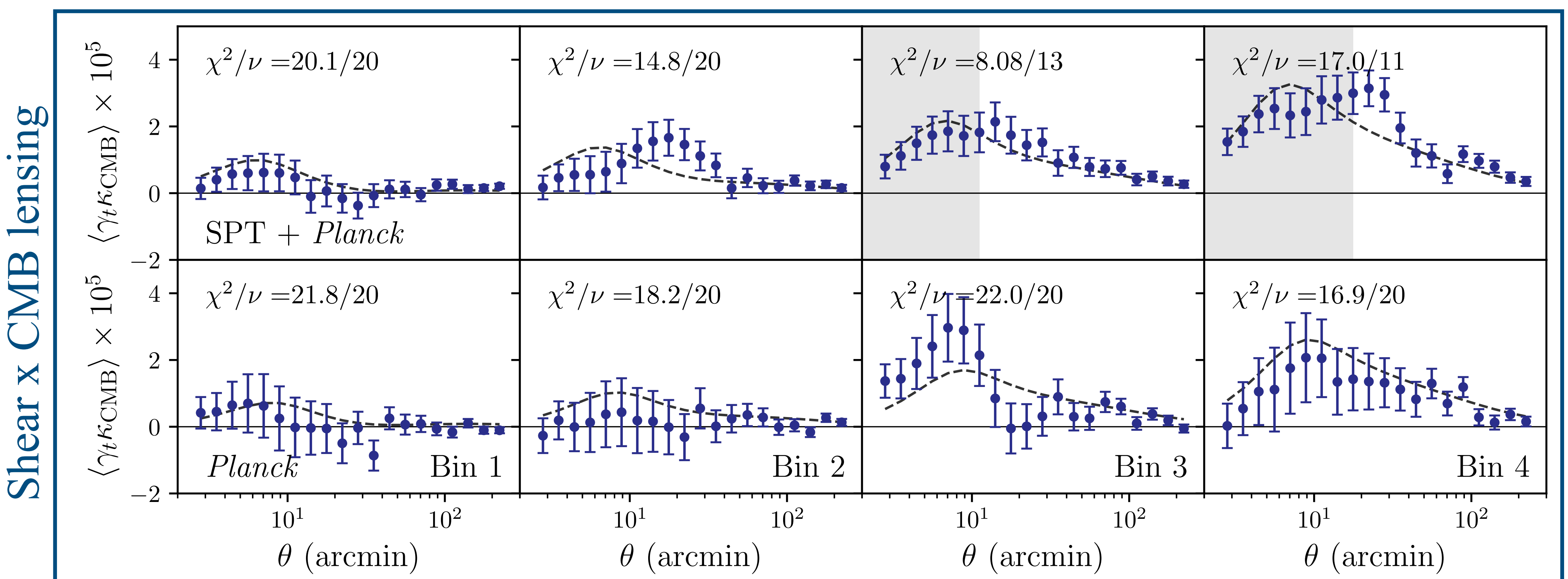


Omori et al. 2022

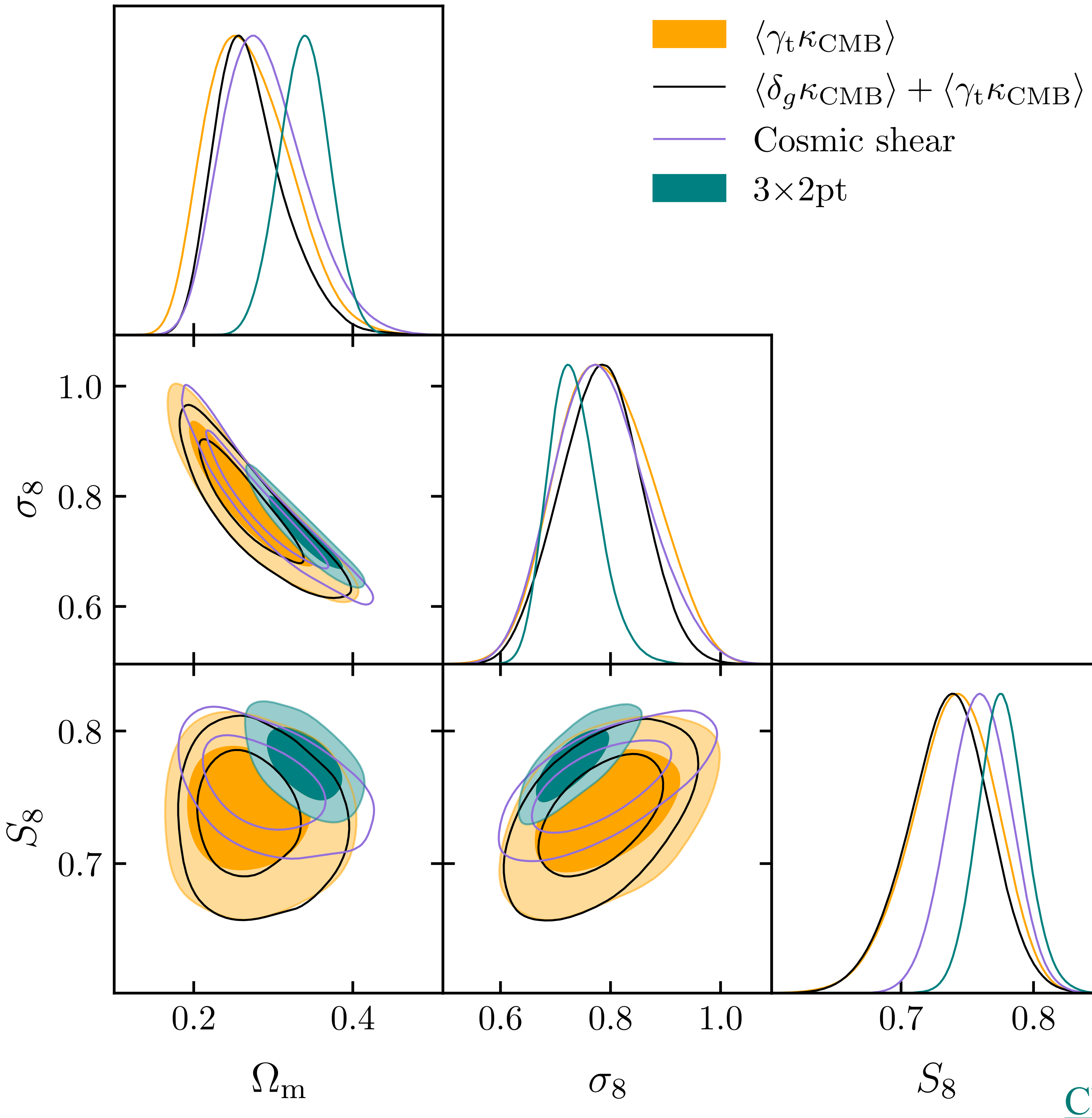
Measurements

Chang et al. 2022



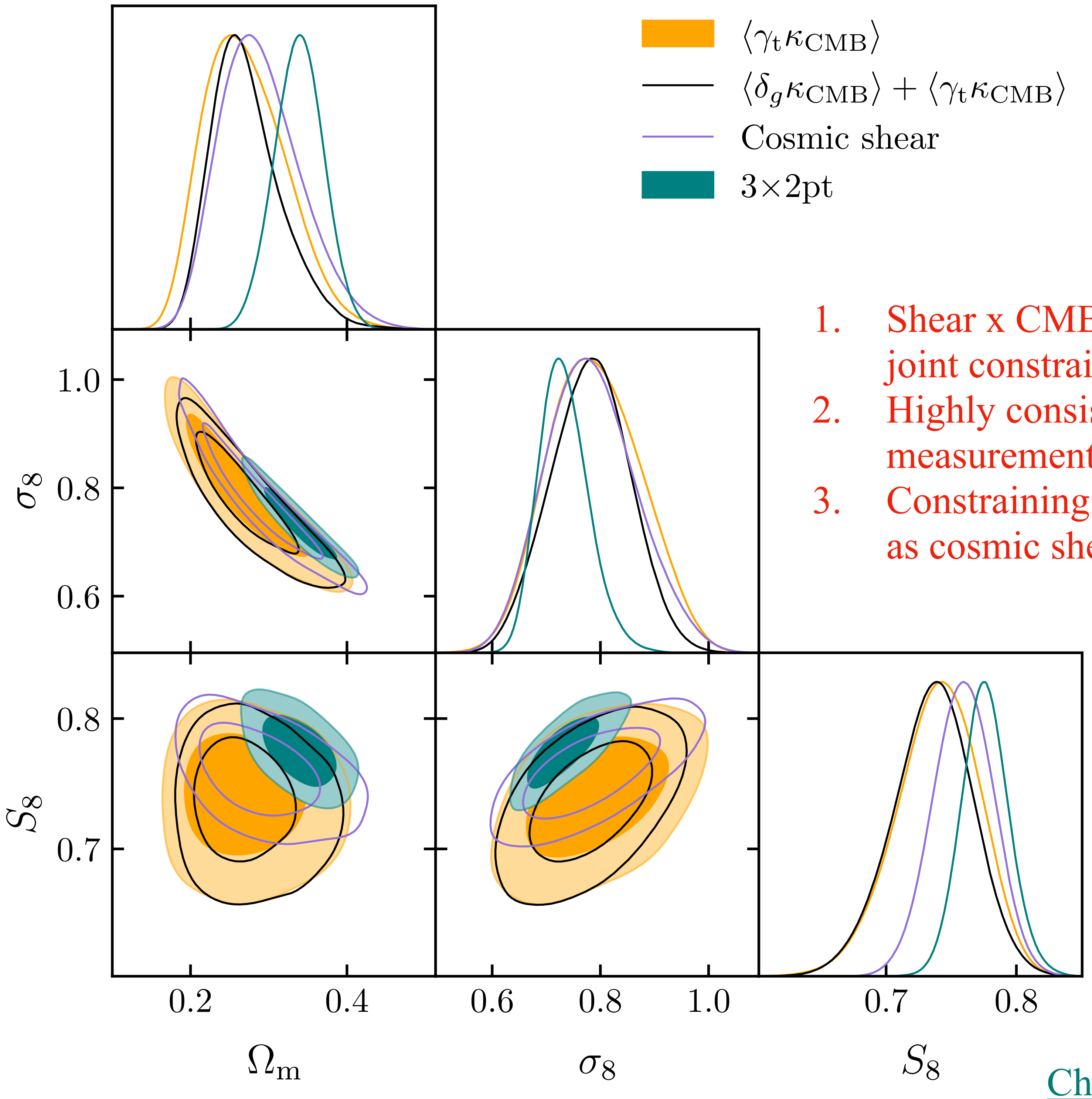


Constraints



Chang et al. 2022

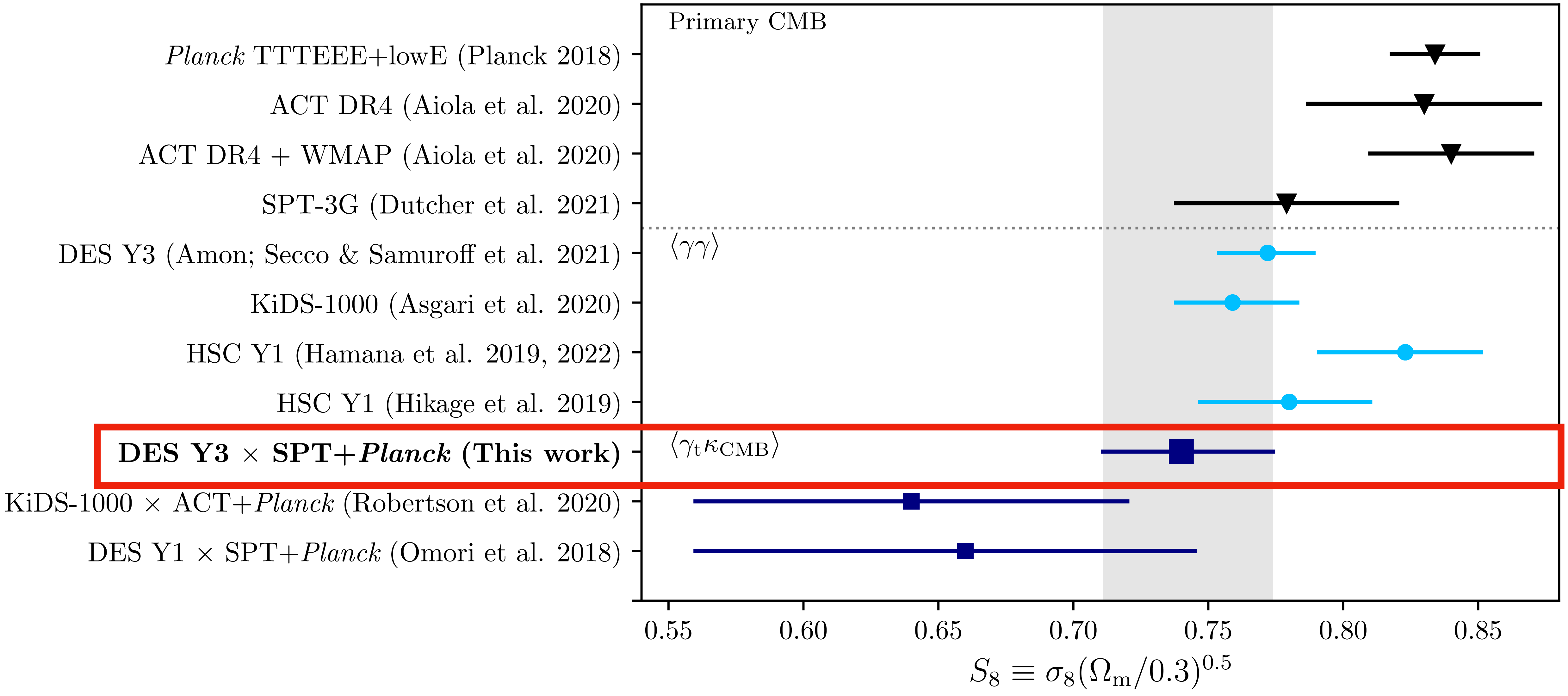
Constraints



1. Shear x CMB lensing dominates the joint constraints
2. Highly consistent with cosmic shear measurements
3. Constraining power is the same order as cosmic shear

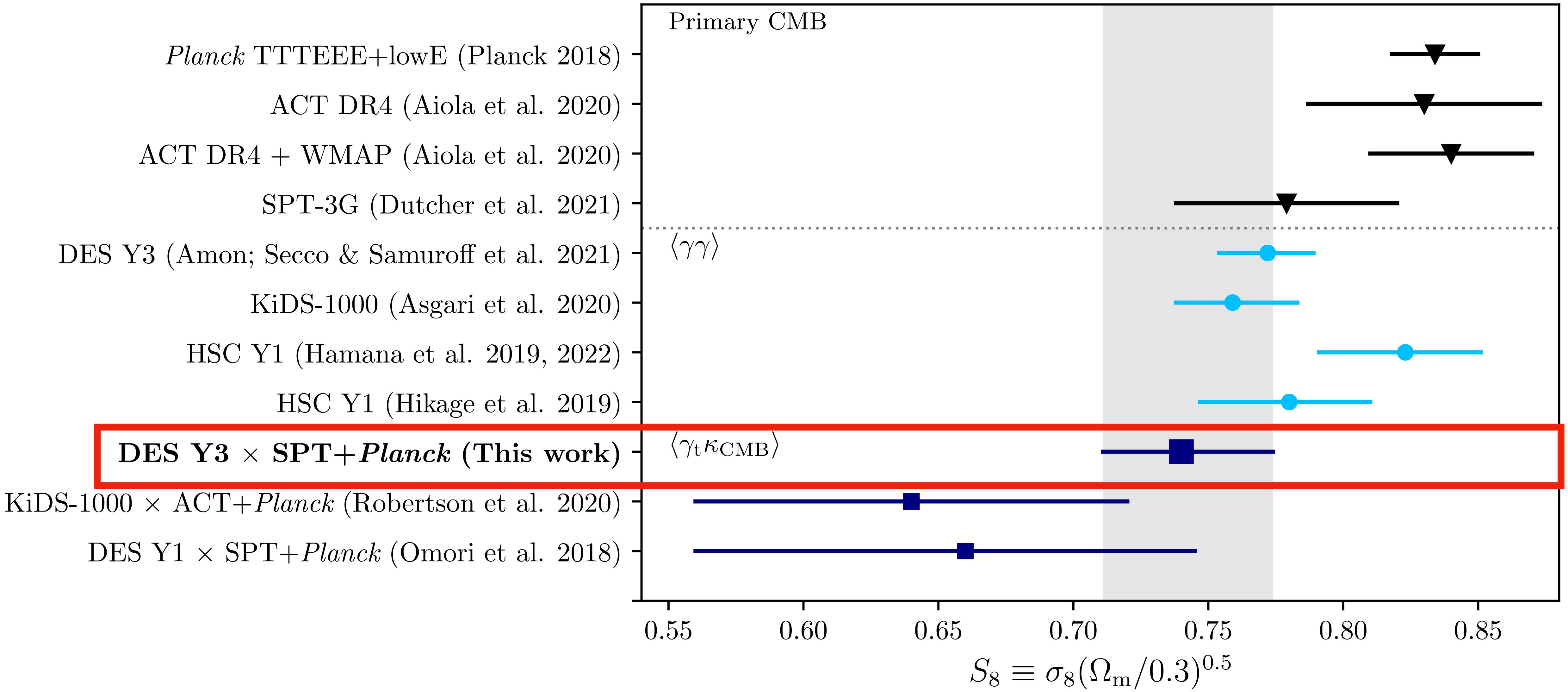
Chang et al. 2022

Comparison with other surveys



Chang et al. 2022

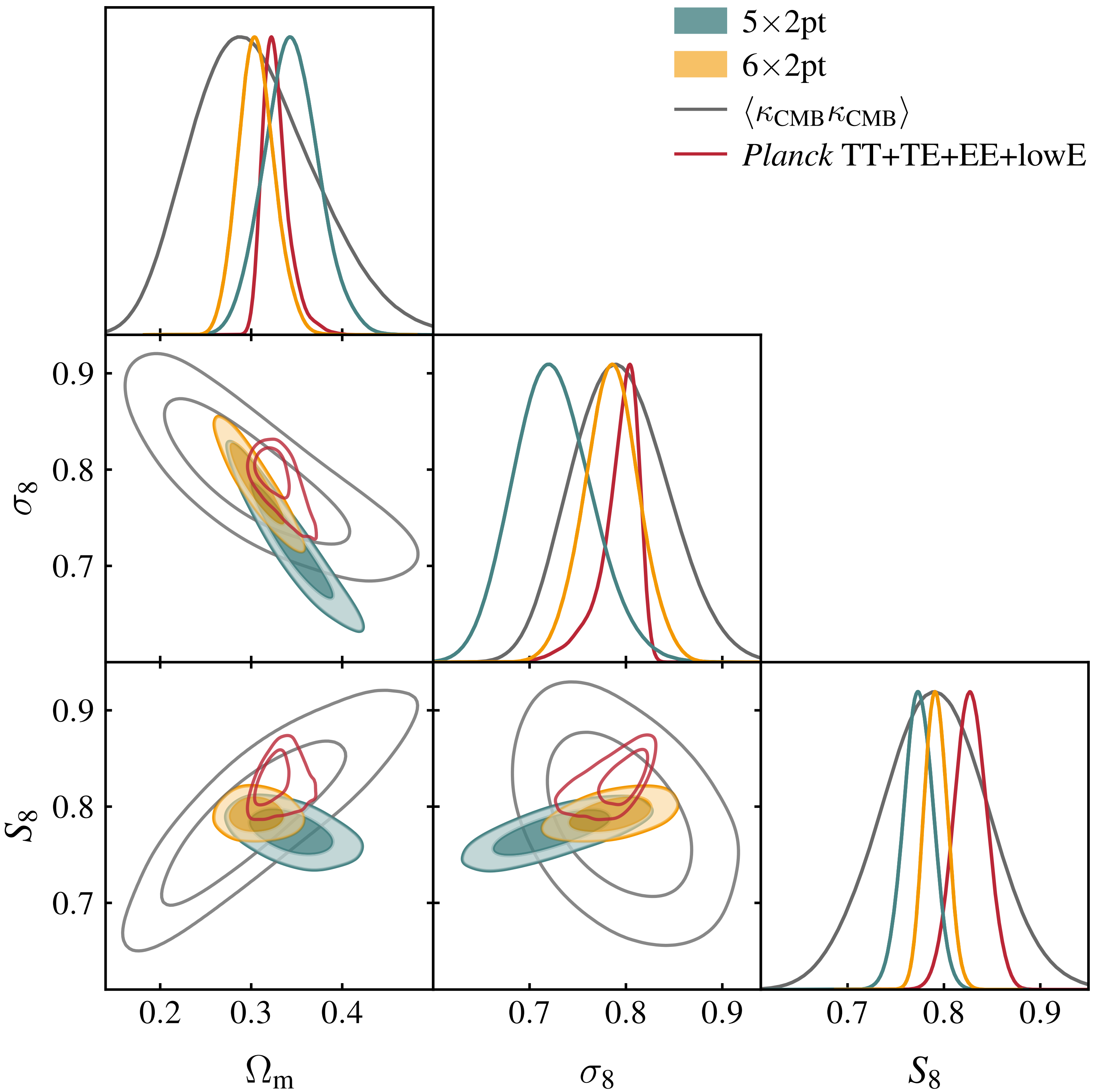
Comparison with other surveys



Chang et al. 2022

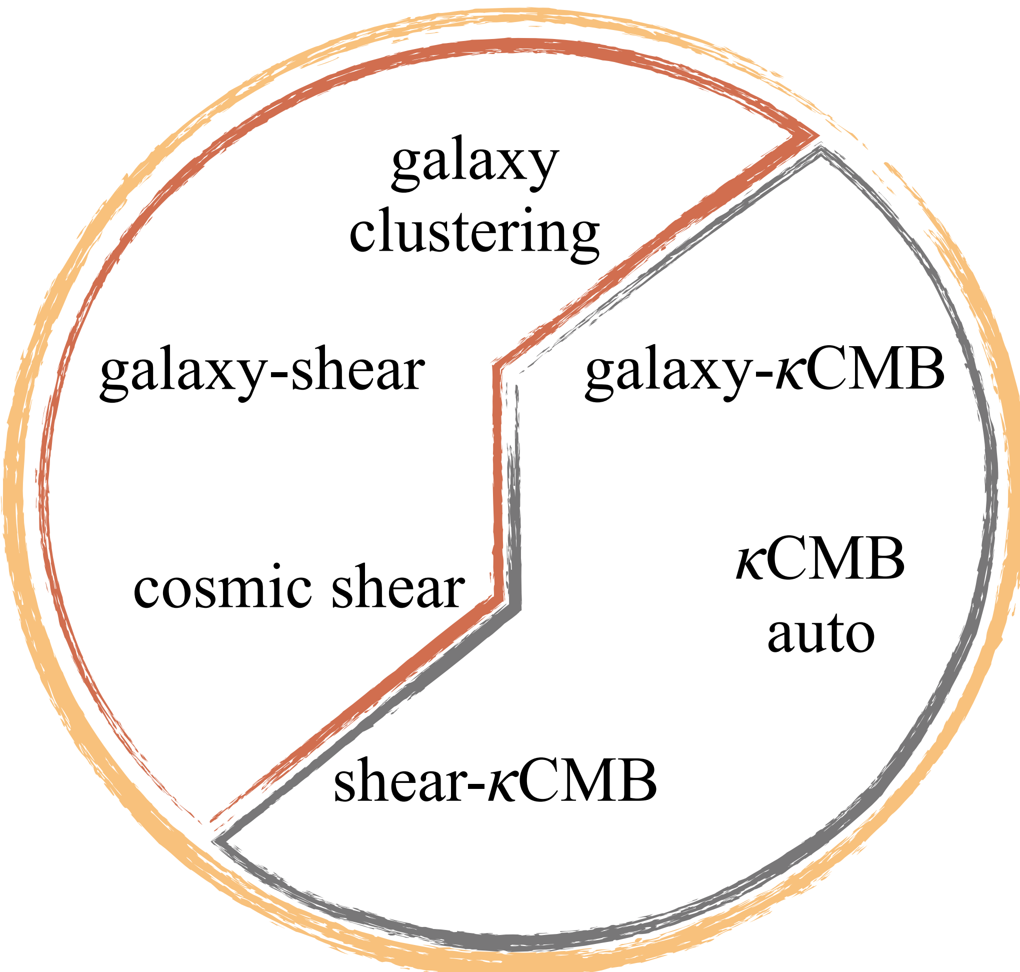
1. Factor of ~3 improvement compared to Y1
2. 1-sigma consistent with cosmic shear

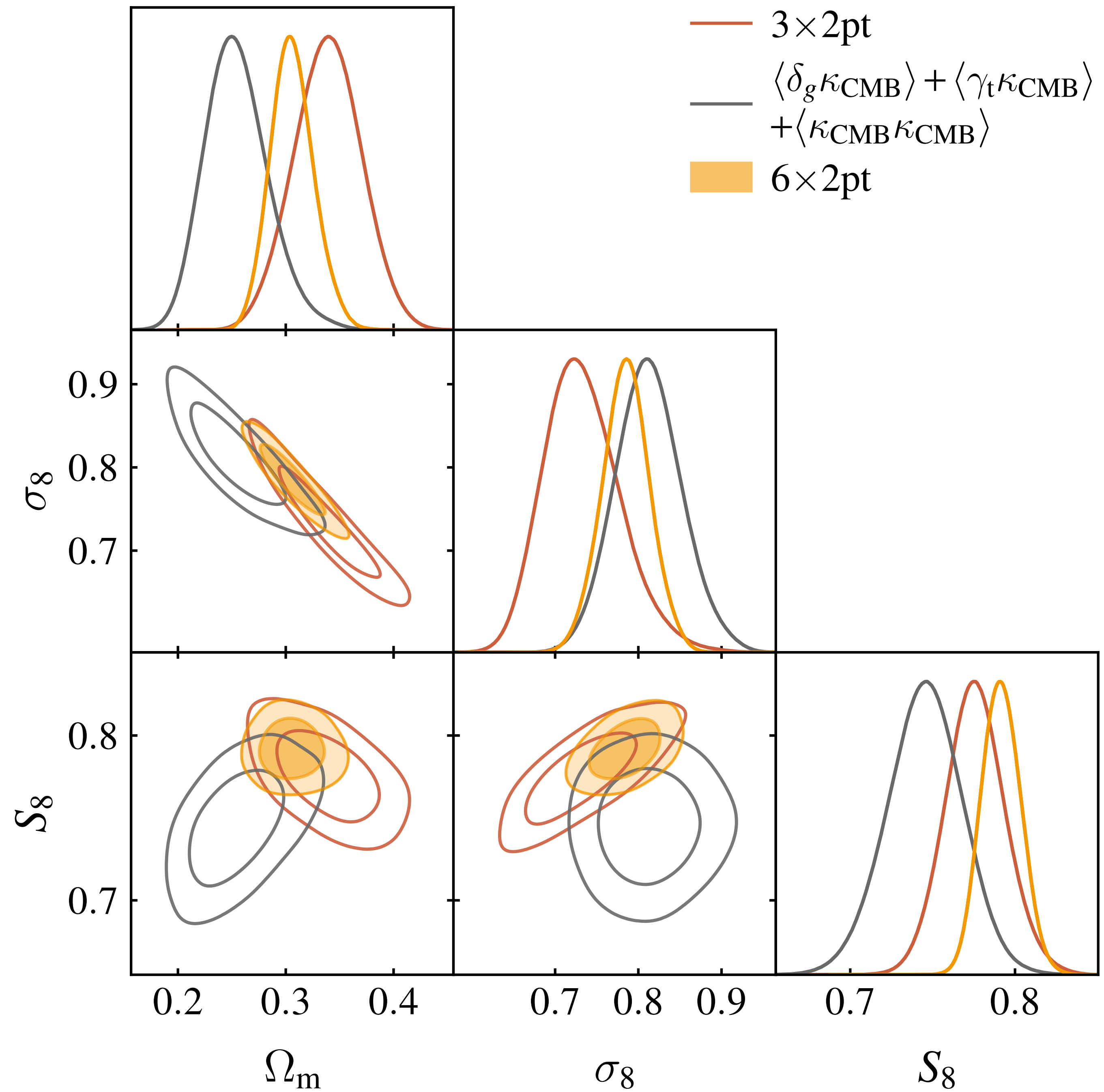
Main combined results



DES & SPT Collaborations 2022

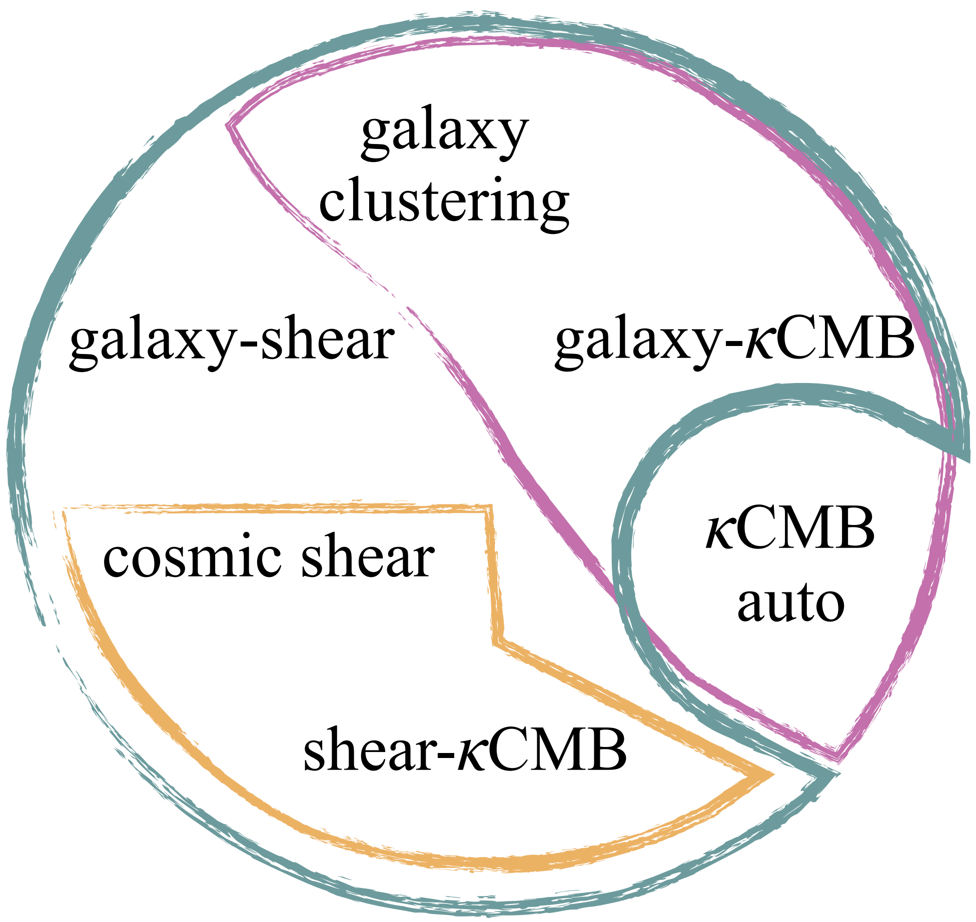
Results: 3x2pt vs "other 3x2pt" vs 6x2pt

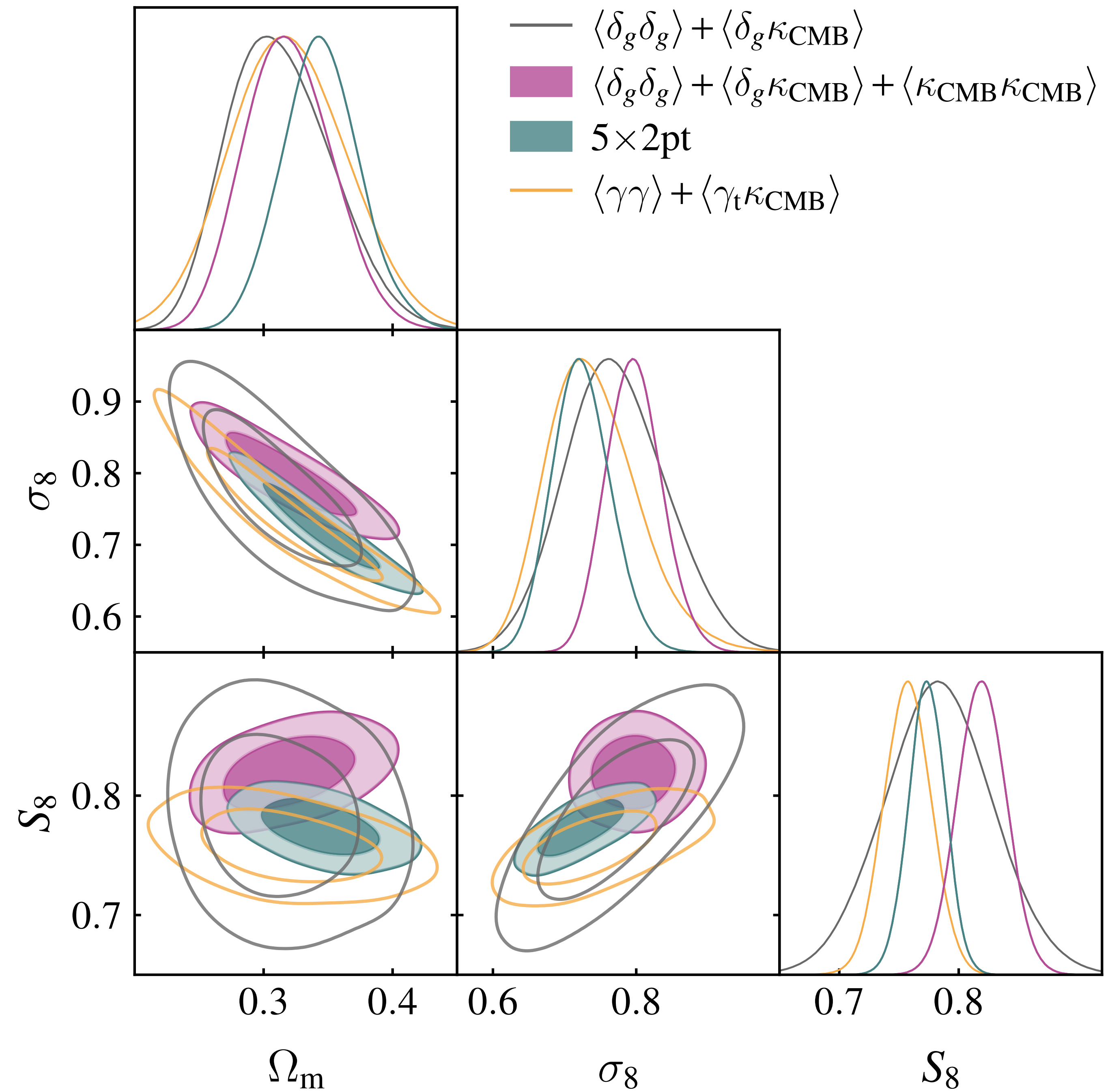




DES & SPT Collaborations 2022

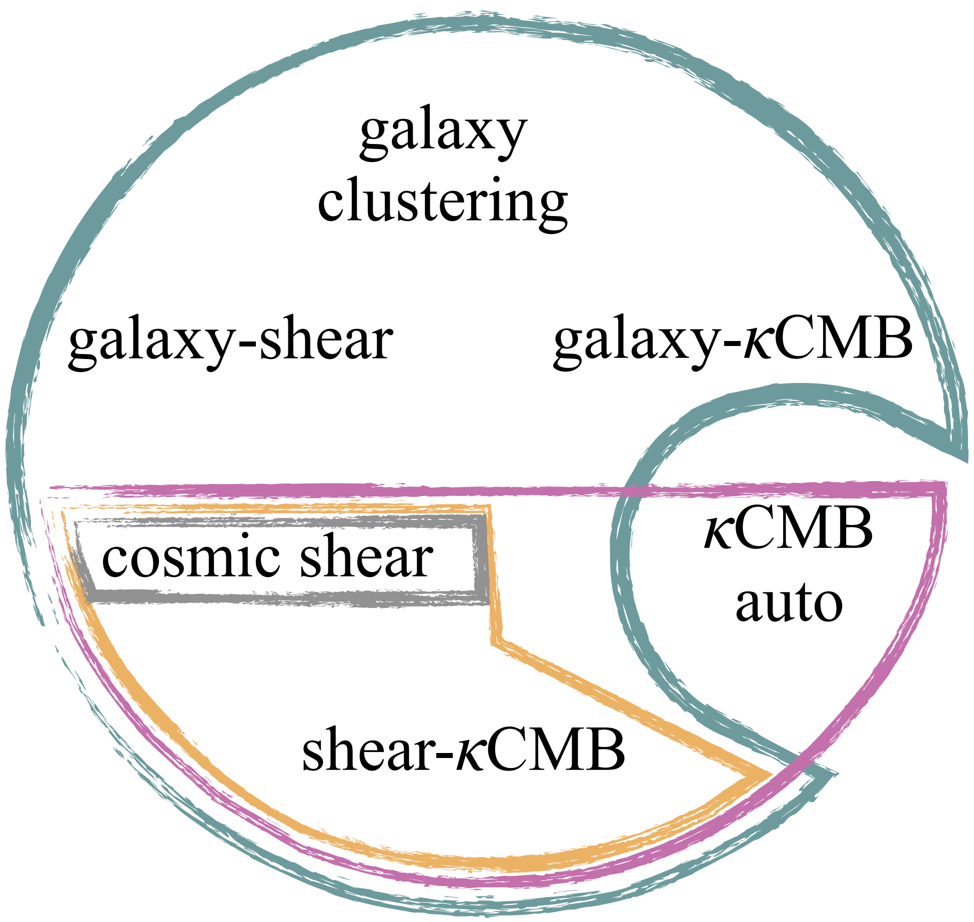
Results: 3x2pt vs "no gal lensing" vs 5x2pt vs "gal lensing"

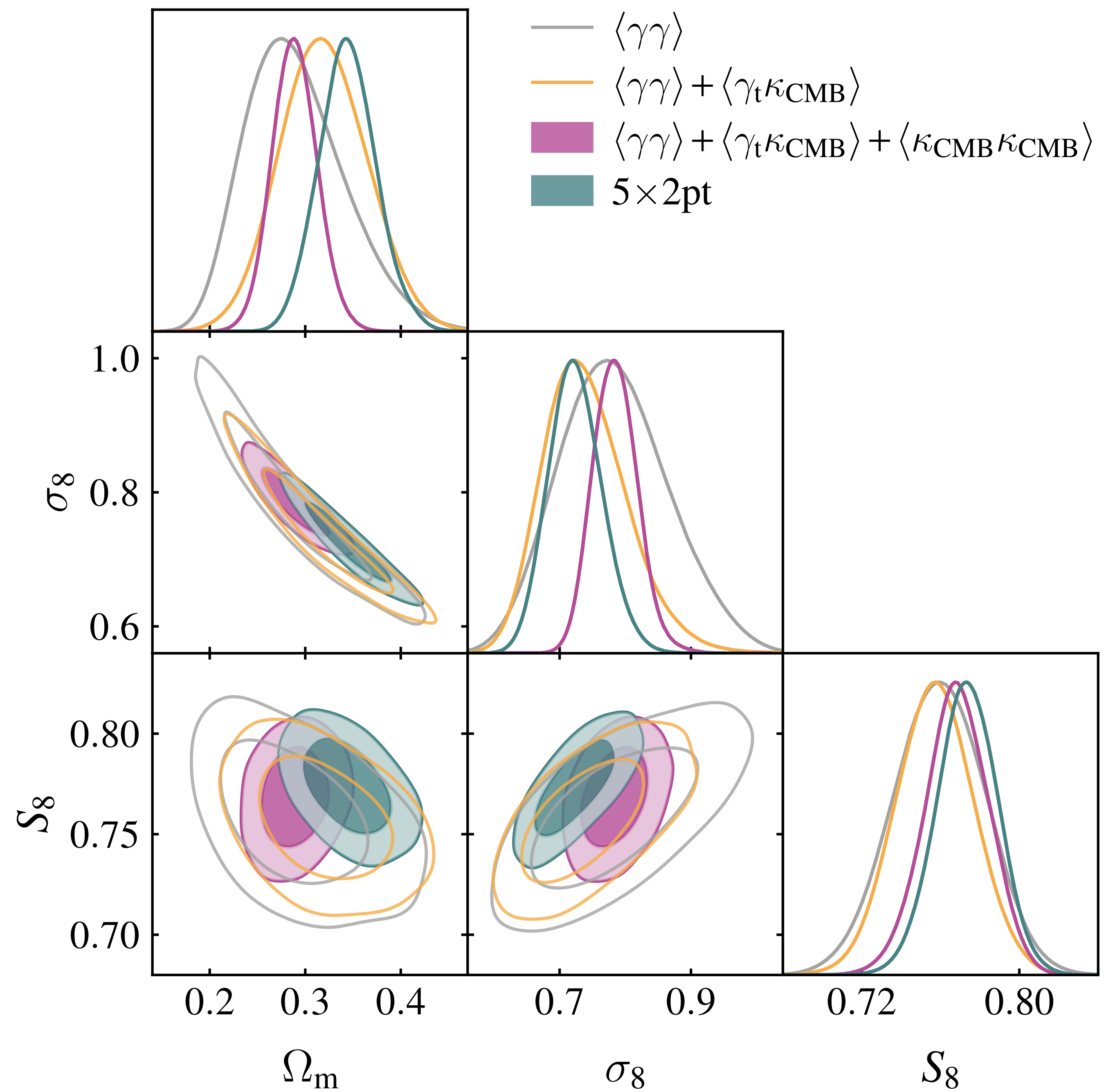




DES & SPT Collaborations 2022

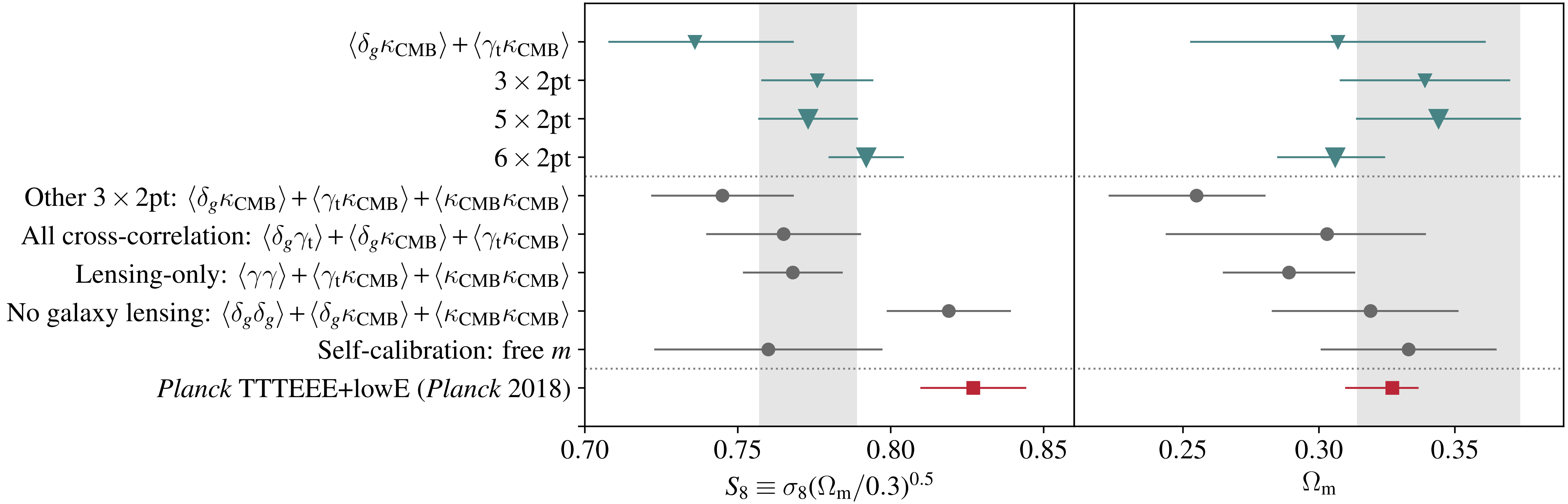
Results: Lensing only





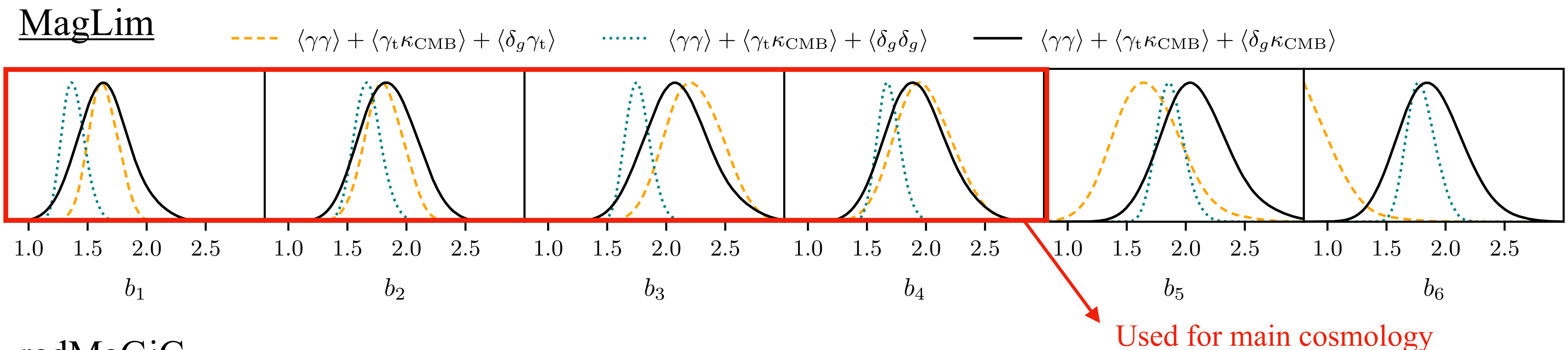
DES & SPT Collaborations 2022

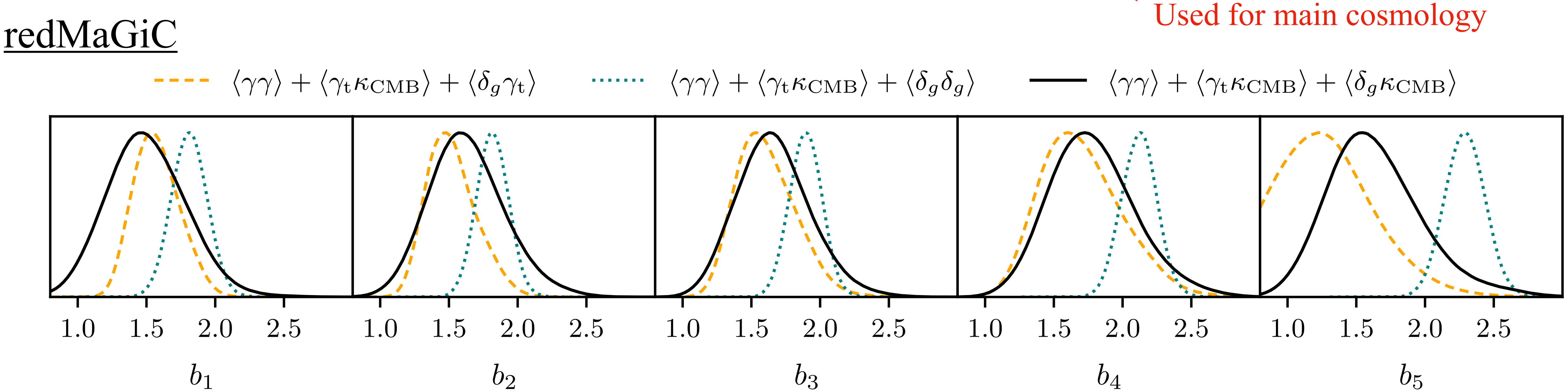
Main combined results



[DES & SPT Collaborations 2022](#)

Investigating lens sample issues





DES & SPT Collaborations 2022

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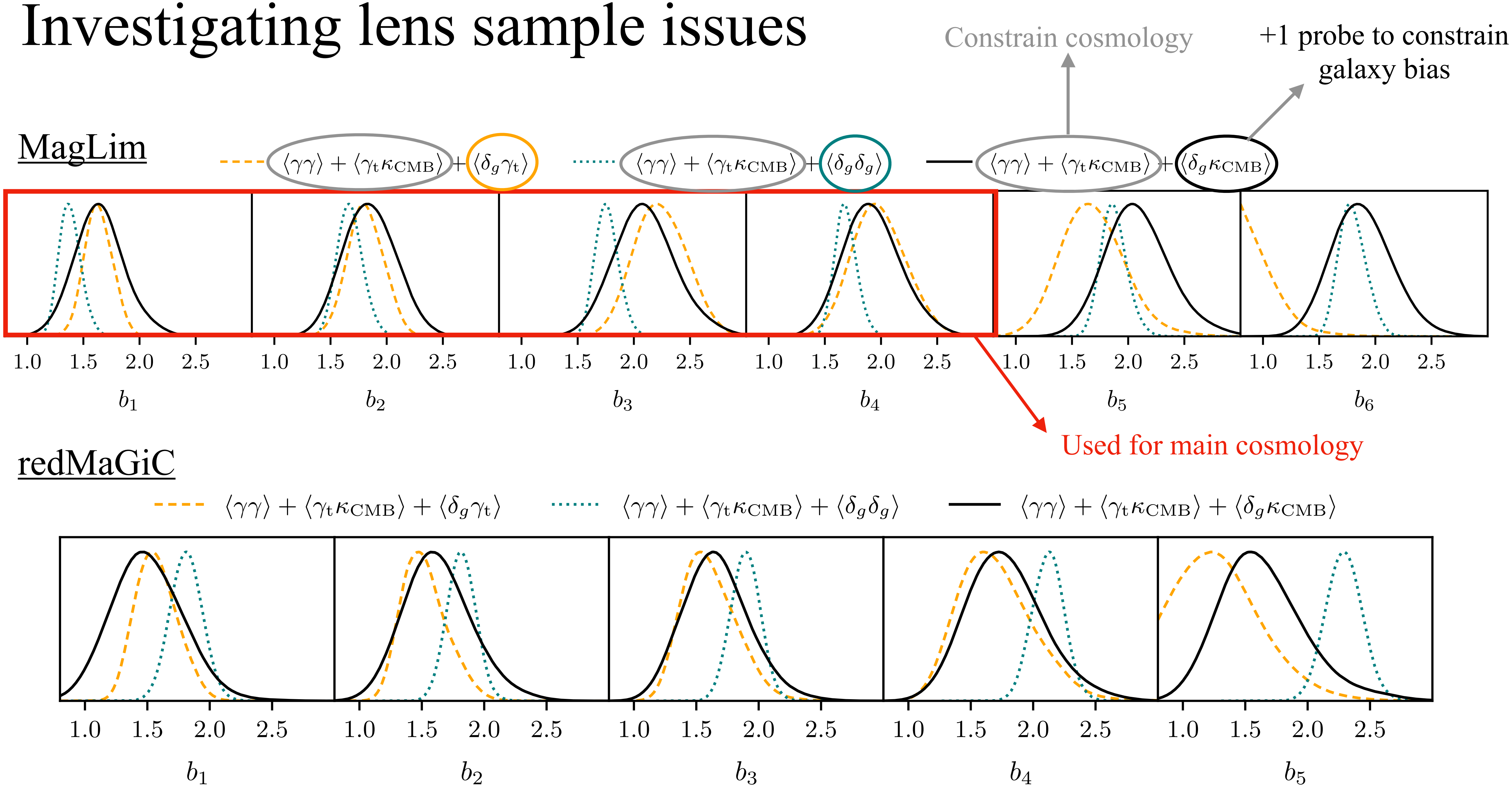
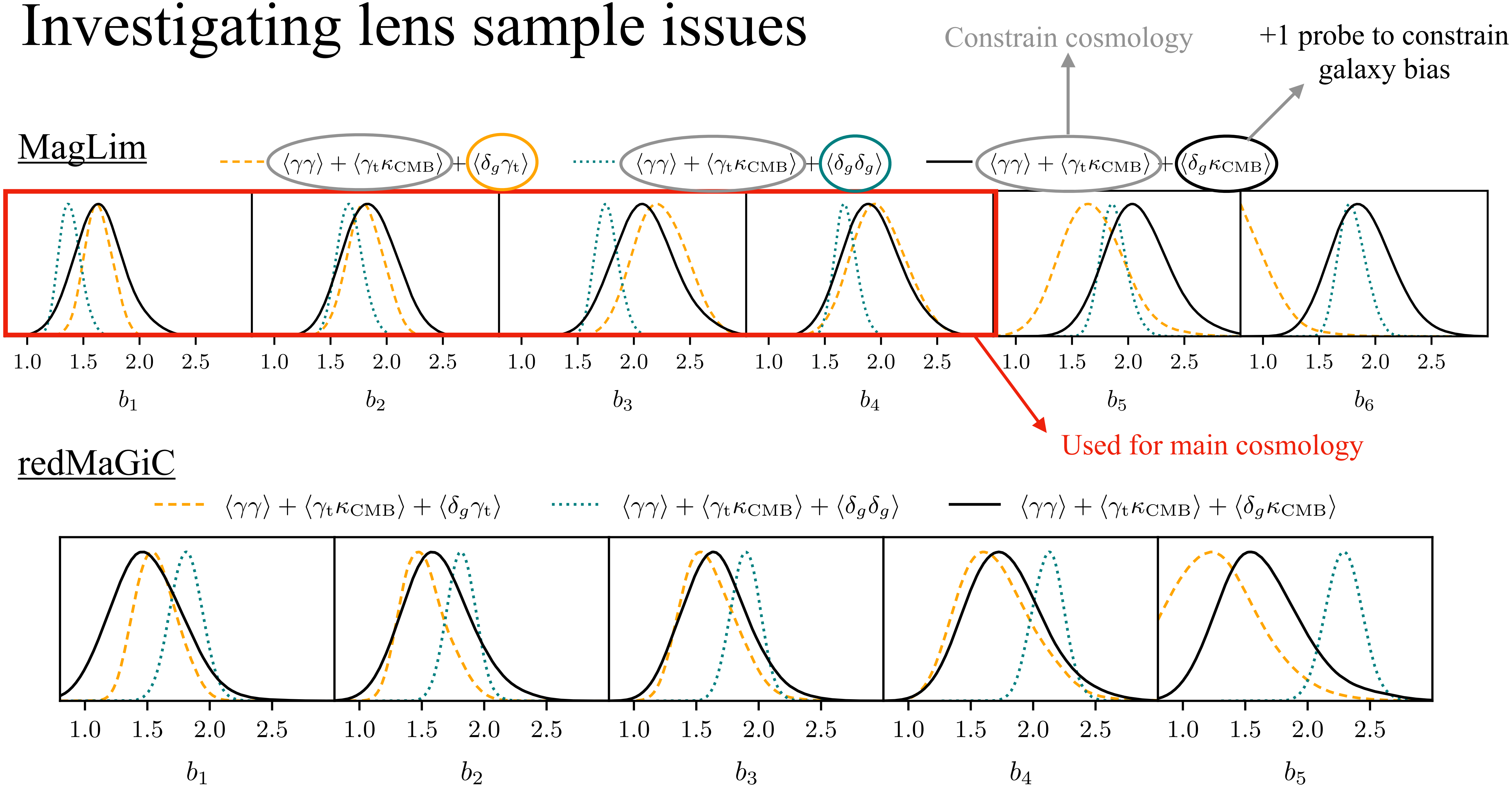


DES & SPT Collaborations 2022

Investigating lens sample issues



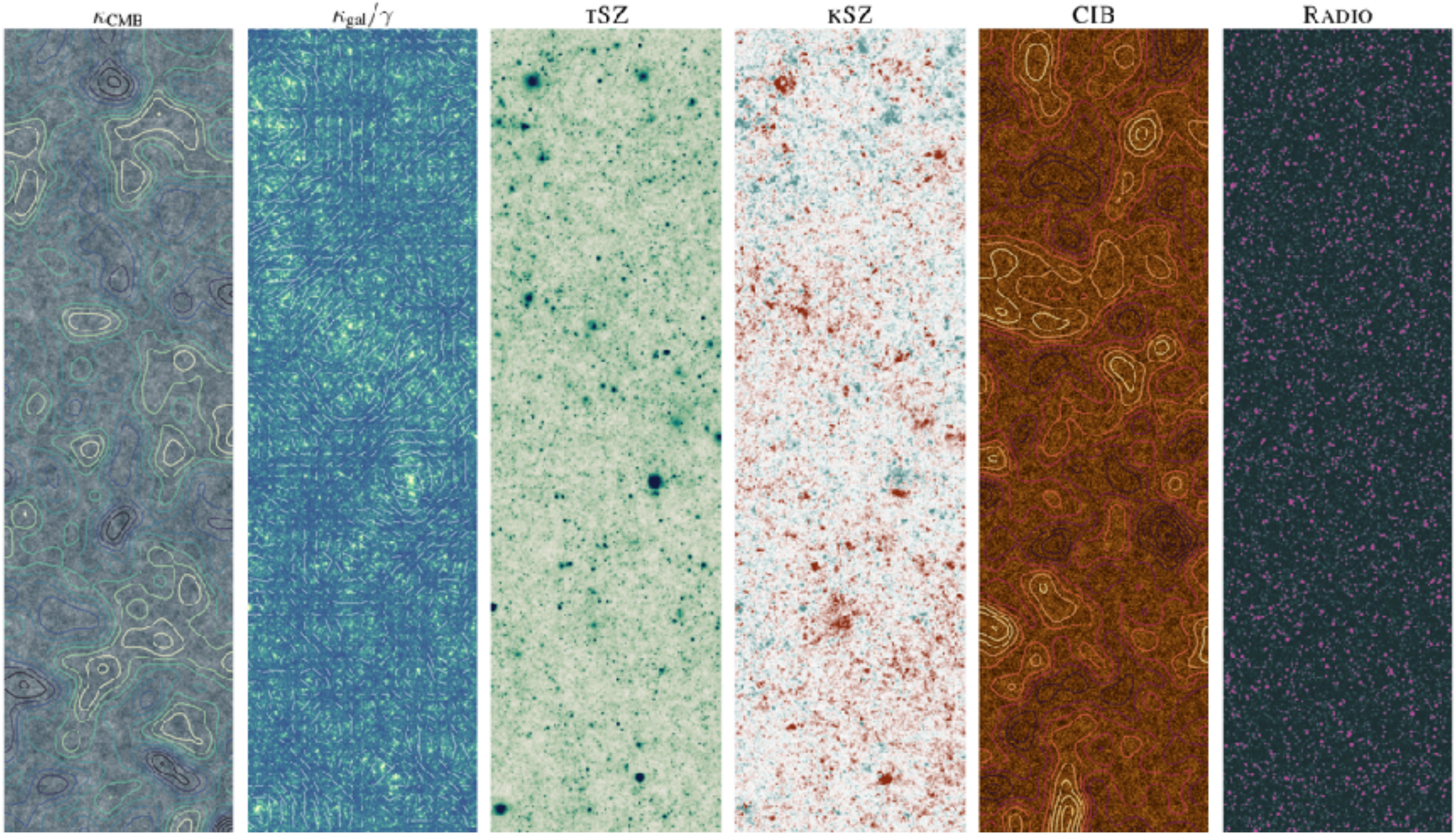
DES & SPT Collaborations 2022

Our constraints are mild so we do not have a definitive answer, but…

- For MagLim, bias values agree more with gg-lensing except the last two bin where the results match better with clustering.
- For redMaGiC, bias values agree more with gg-lensing.

Part I summary

- DES uses galaxy position/shear information to extract cosmology (3×2pt)
- By cross-correlating with CMB lensing maps we get an addition three 2pt functions (i.e. 6×2pt).
- Significant improvements were made:
  - Improvement of the CMB lensing map (tSZ nulling)
  - Y3 coverage
- shear × CMB lensing dominates the constraing power over galaxy × CMB lensing.
- Cosmological constraints from combing the two cross-correlation probes is competetive with cosmic shear measurements (so we can use it to test for systematic errors in DES data).
- The combined cosmological constraints are consistent with *Planck* primary constraints.



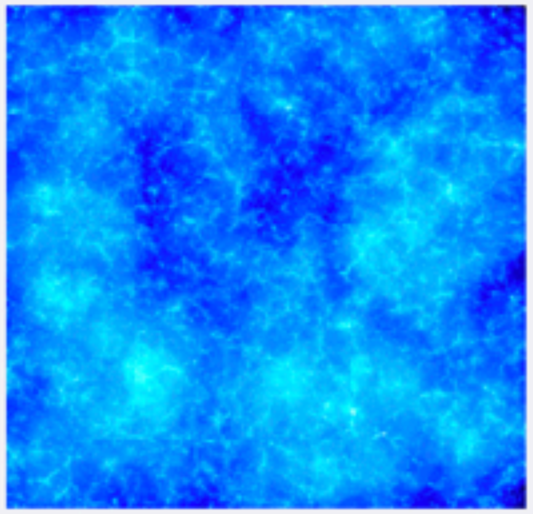
Part II: MultiDark Planck 2 Synthetic Sky Simulation

MDPL2

MDPL2

The MultiDark Planck 2 simulation belongs to the series of MultiDark simulations with Planck cosmology. It is kin to the MDPL simulation, with the same box size, cosmological parameters and particle resolution, but a different initial seed.
If you are in doubt whether to use MDPL or MDPL2, we recommend to use MDPL2, since there will be more data products available for this simulation in the future (e.g. Rockstar-catalogues).

Please give proper Credits when using data from this simulation.



FOF-halos from a slice of MDPL2 at redshift z=0. More images

https://www.cosmosim.org/cms/simulations/mdpl2/

- Publicly available dark matter only N-body simulation.
- Rockstar halo catalogs, semi-analytic galaxy catalogs are available online.

Configuration	
Box size	$1\ h^{-1}$Gpc
N_{part}	3840^3
Mass resolution	$1.51 \times 10^9\ h^{-1}\mathrm{M}_\odot$
Force resolution	$\sim 15\ h^{-1}$kpc (at high z)
	$\sim 8\ h^{-1}$kpc (at low z)
Initial redshift	120
N_{snap}	130

CMB components

Implemented CMB secondaries:

- Thermal Sunyaev Zel'dovich effect (tSZ)
- Kinetic Sunyaev Zel'dovich effect (kSZ)
- Cosmic infrared background (CIB) and IR sources
- Radio galaxies
- CMB lensing from ray-tracing
- galactic foregrounds from PySM3

LSS components

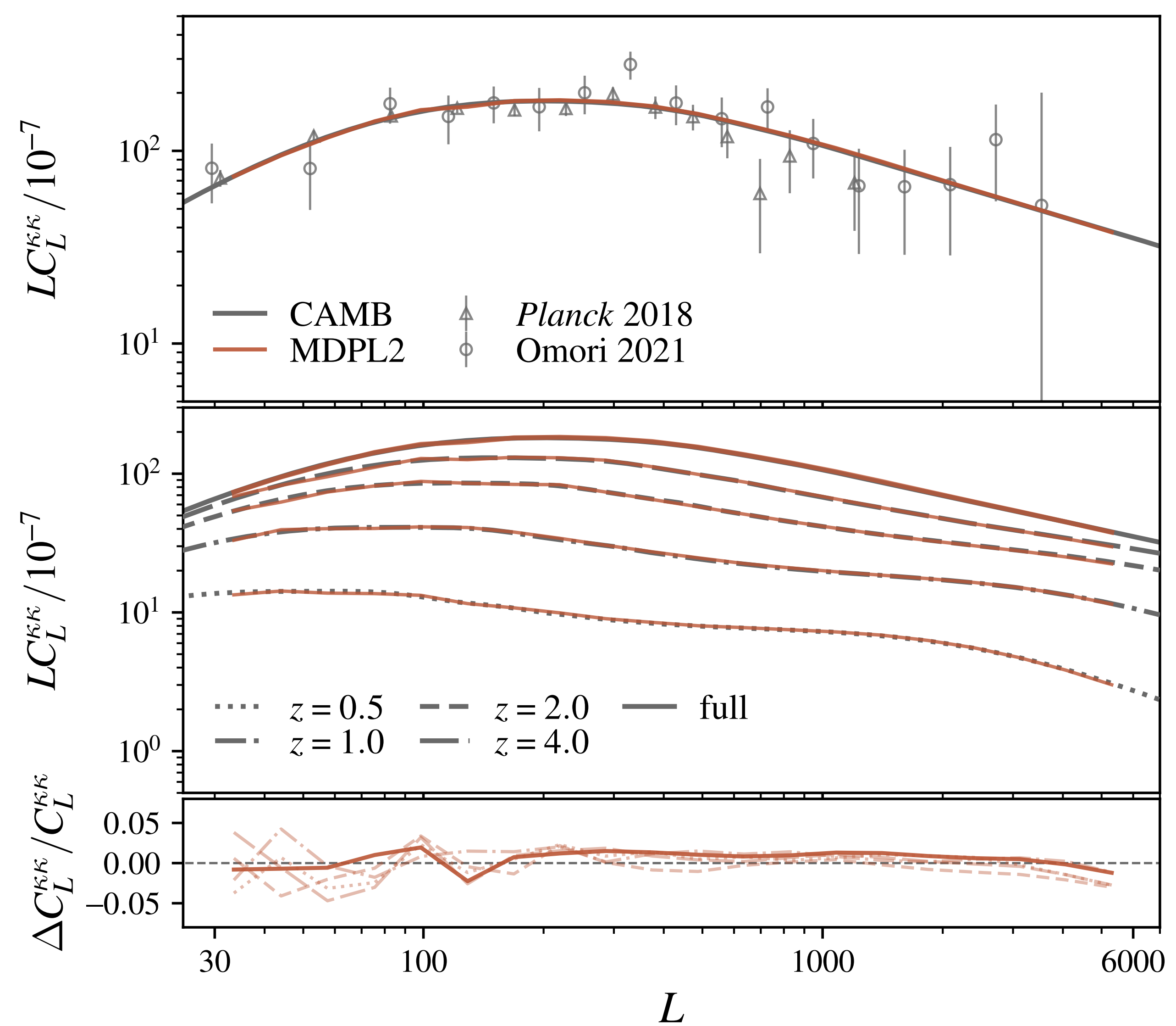
- Lens galaxies:
  BYO HOD: various groups have used MDPL2 to implement galaxies including BOSS & DESI. Some people are working on implementing DES-Y3 MagLim sample. Also have DES-Y1/DES-Y3/LSST-Y1 Poisson sampled galaxies.

- Source galaxies:
  Shear signal from ray-tracing, with noise added by randomly rotating e_1, e_2 from data or σ_e values (includes NLA IA). Currently have DES-Y1/DES-Y3/LSST-Y1 mock catalogs.

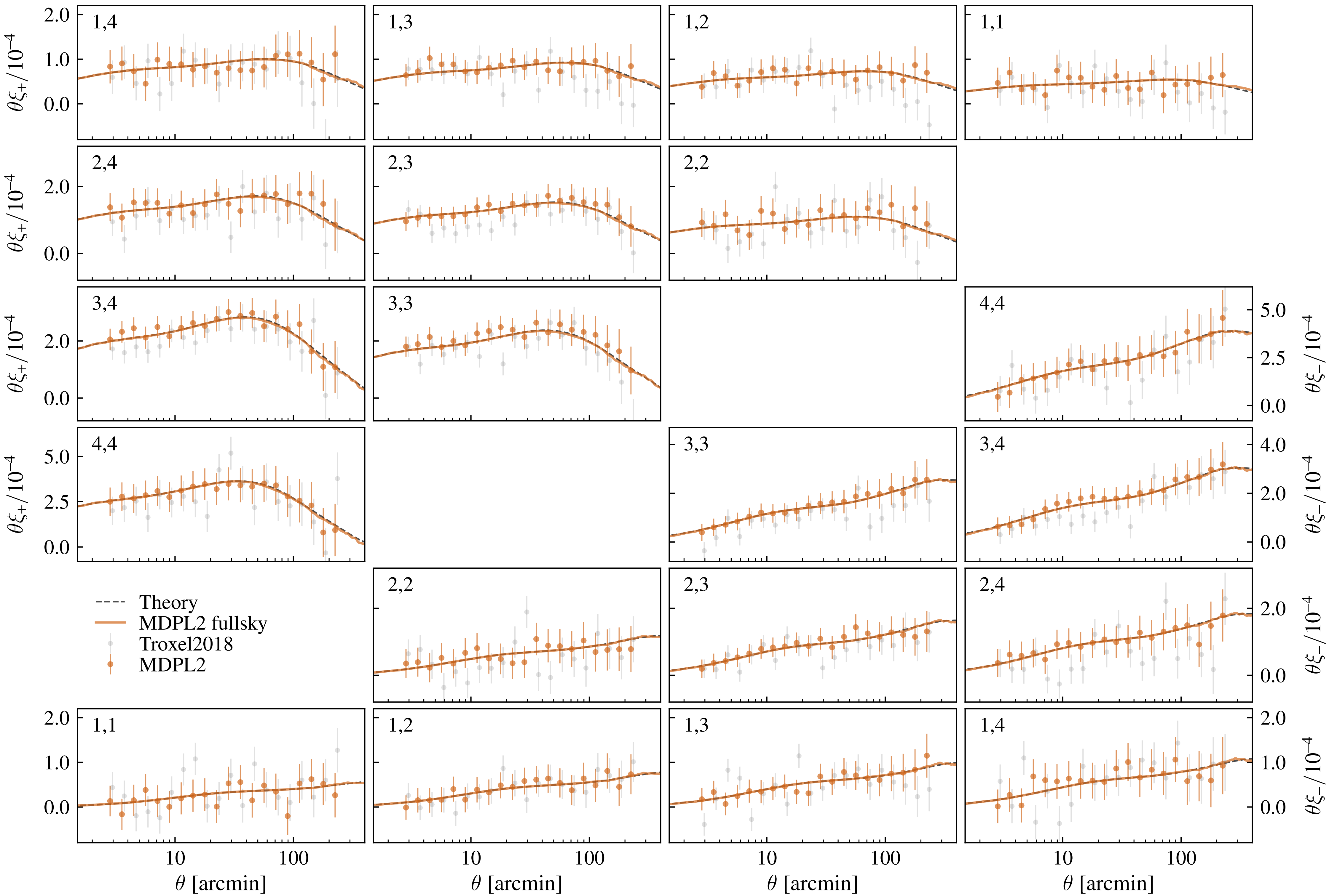
Lensing components

To produce the lensing maps:

1. Project all the particles onto HEALPix shells of width of 25 Mpc/*h*.
2. Apply rotation every 1Gpc/*h* to avoid repeating structure.
3. Run raytracing at *N*side=16384.
4. Both galaxy and CMB lensing are processed up to *z*=8.6, and a Gaussian component is added to CMB lensing (to cover 8.6<*z*<1100).

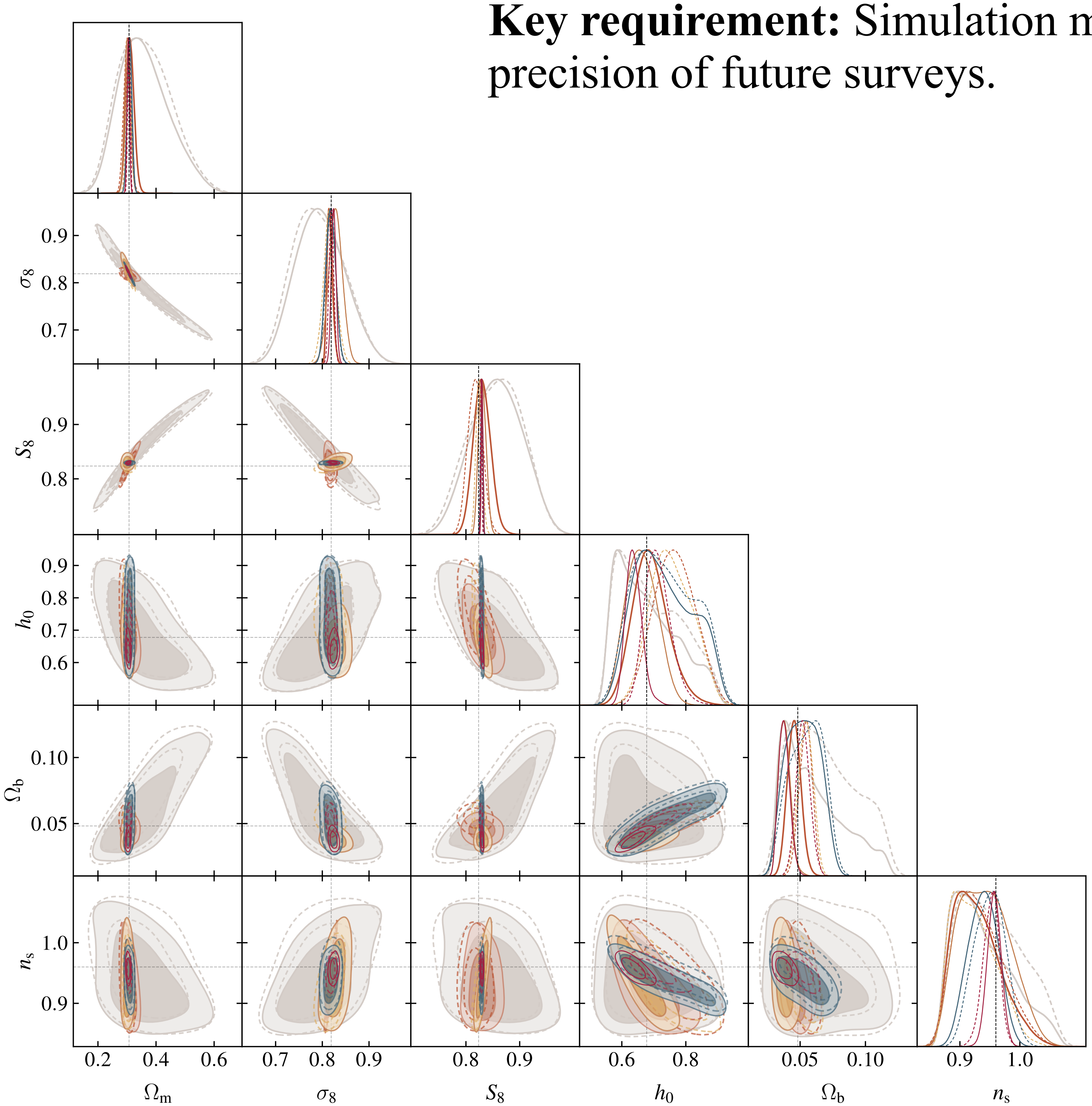


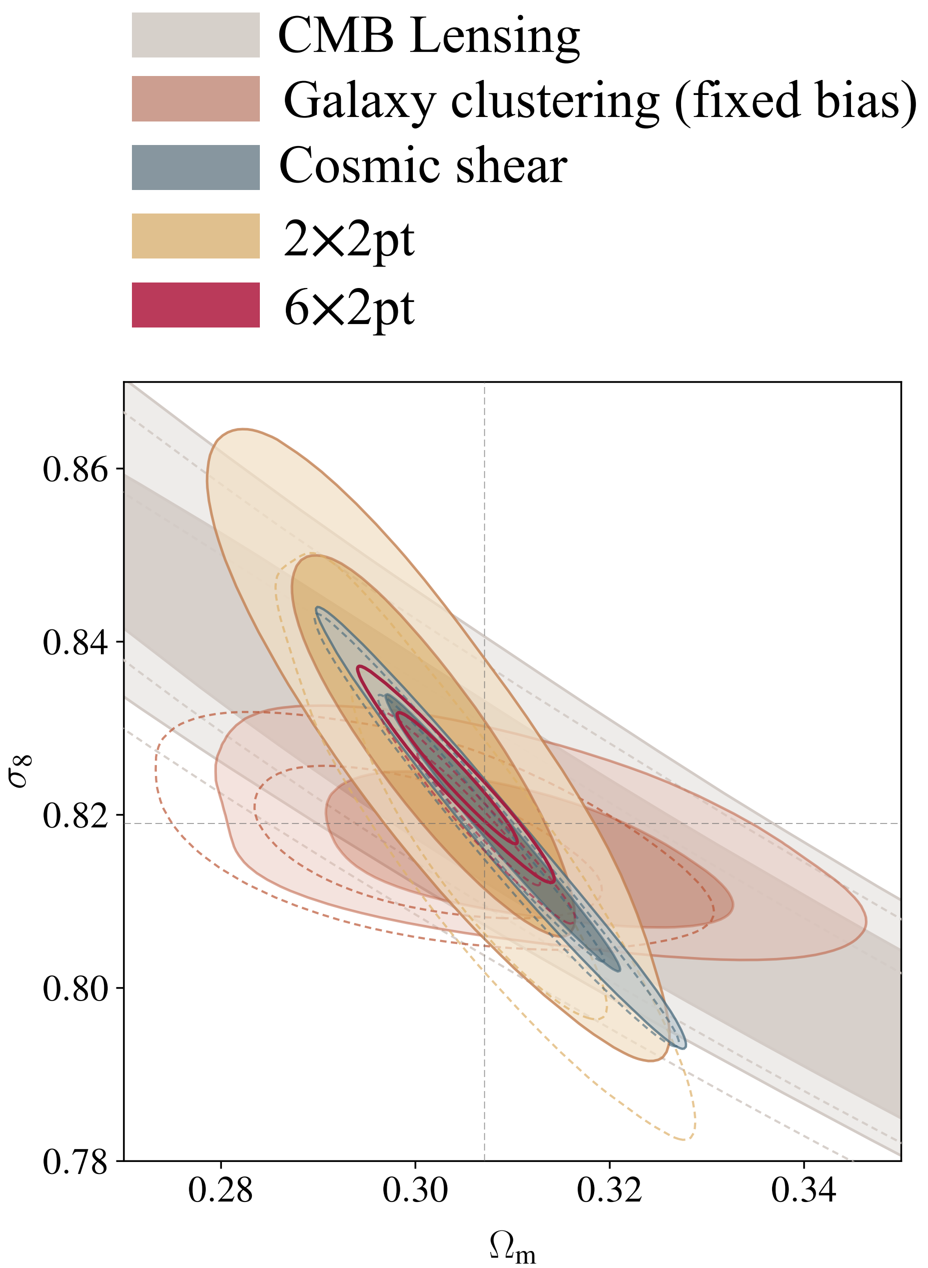
Lensing components



Lensing components

Key requirement: Simulation must return input cosmology at the precision of future surveys.





Implementation: tSZ

The tSZ map is generated using the MDPL2 Rockstar halo catalog and using the Mead2020 model, which is calibrated against the BAHAMAS simulation (McCarthy 2016).

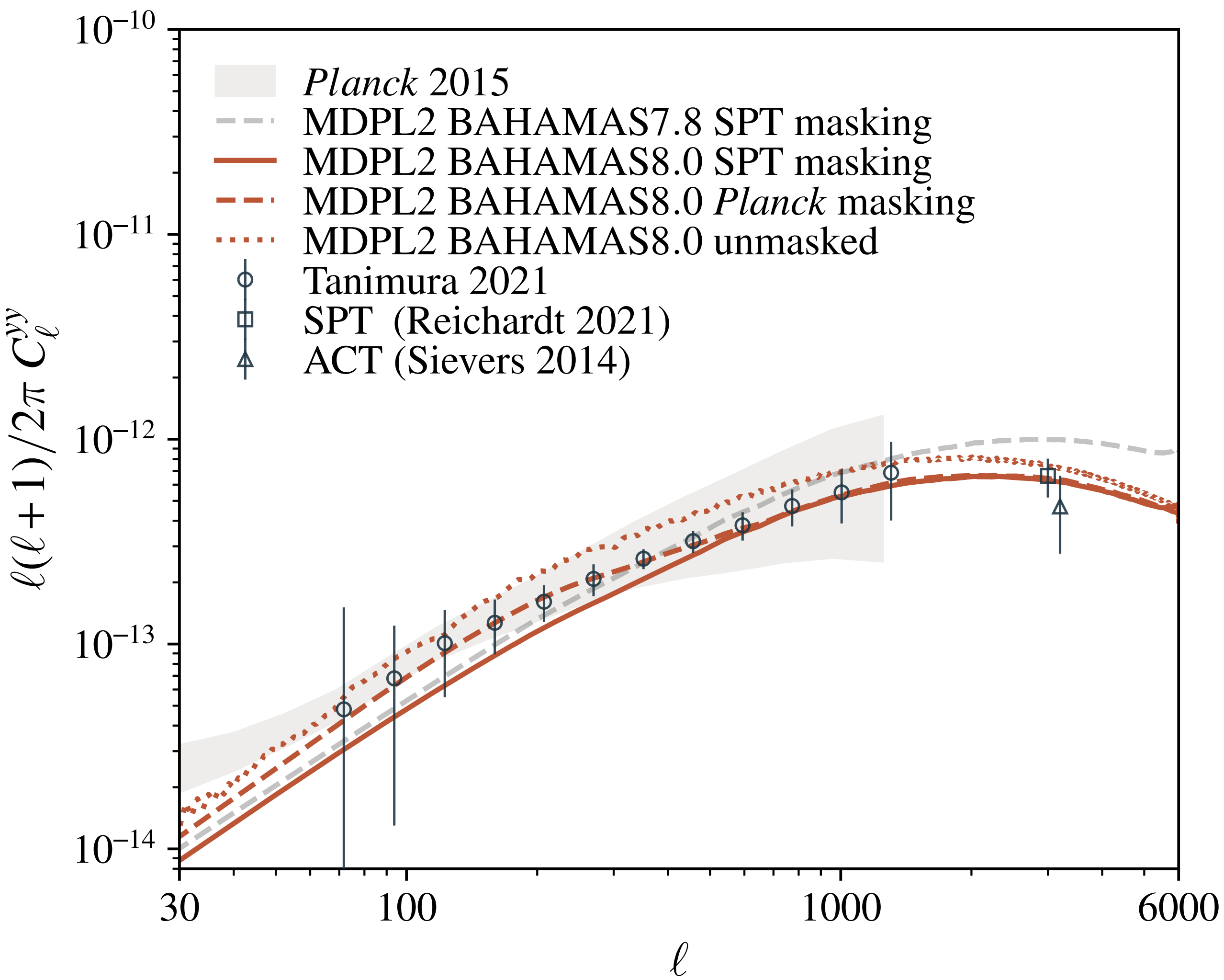
$$y(\hat{n}) = \frac{\sigma_T}{m_e c^2} \int_{\mathrm{LOS}} dl \; P_e$$

$$P_e^{\mathrm{bnd}}(M_{\mathrm{vir}}, r) = \frac{\rho_{\mathrm{gas}}^{\mathrm{bnd}}(M_{\mathrm{vir}}, r)}{m_p \mu_e} k_B T_{\mathrm{gas}}(M_{\mathrm{vir}}, r)$$

$$\rho_{\mathrm{gas}}^{\mathrm{bnd}}(M_{\mathrm{vir}}, r) = \rho_0 \left[\frac{\ln(1 + r/r_s)}{r/r_s} \right]^{1/\Gamma - 1}$$

Currently using the $T_{\mathrm{AGN}} = 10^{8.0}$K model as the default (see e.g. Tröester2021).

Parameter	$10^{7.6}$ [K]	$10^{7.8}$ [K]	$10^{8.0}$ [K]
ϵ_0	-0.1002	-0.1065	-0.1253
ϵ_1	-0.0456	-0.1073	-0.0111
Γ	1.1647	1.1770	1.1966
M_0	13.1949	13.5937	14.2480
α	0.7642	0.8471	1.0314
β	0.6	0.6	0.6
$\log(T_{w,0}/K)$	6.6762	6.6545	6.6615
$T_{w,1}$	-0.5566	-0.3652	-0.0617



Implementation: kSZ

The kSZ map is similarly generated using the MDPL2 Rockstar halo catalog and the velocity information from particles and following the Mead2020 model.

$$\left(\frac{\Delta T}{T}\right)_{\rm kSZ} = -\frac{\sigma_{\rm T}}{c}\int_{\rm LOS} dl\ n_{\rm e}\ v_{\rm LOS}$$

$$n_{\rm e} = \frac{\rho_{\rm gas}^{\rm bnd}(M_{\rm vir}, r)}{m_{\rm p}\mu_{\rm e}}$$

$$\rho_{\rm gas}^{\rm bnd}(M_{\rm vir}, r) = \rho_0 \left[\frac{\ln(1 + r/r_{\rm s})}{r/r_{\rm s}}\right]^{1/\Gamma - 1}$$

Parameter	$10^{7.6}$ [K]	$10^{7.8}$ [K]	$10^{8.0}$ [K]
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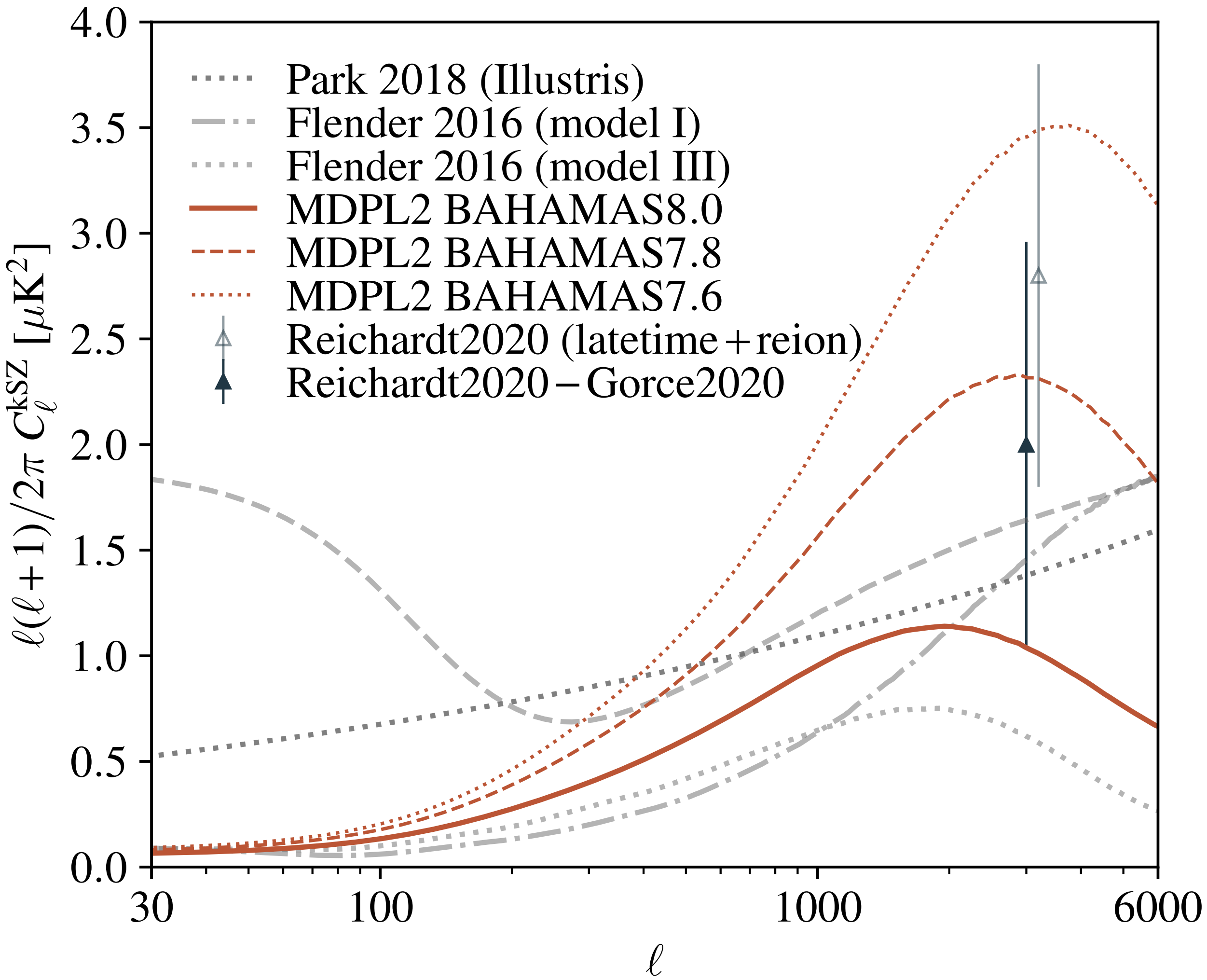
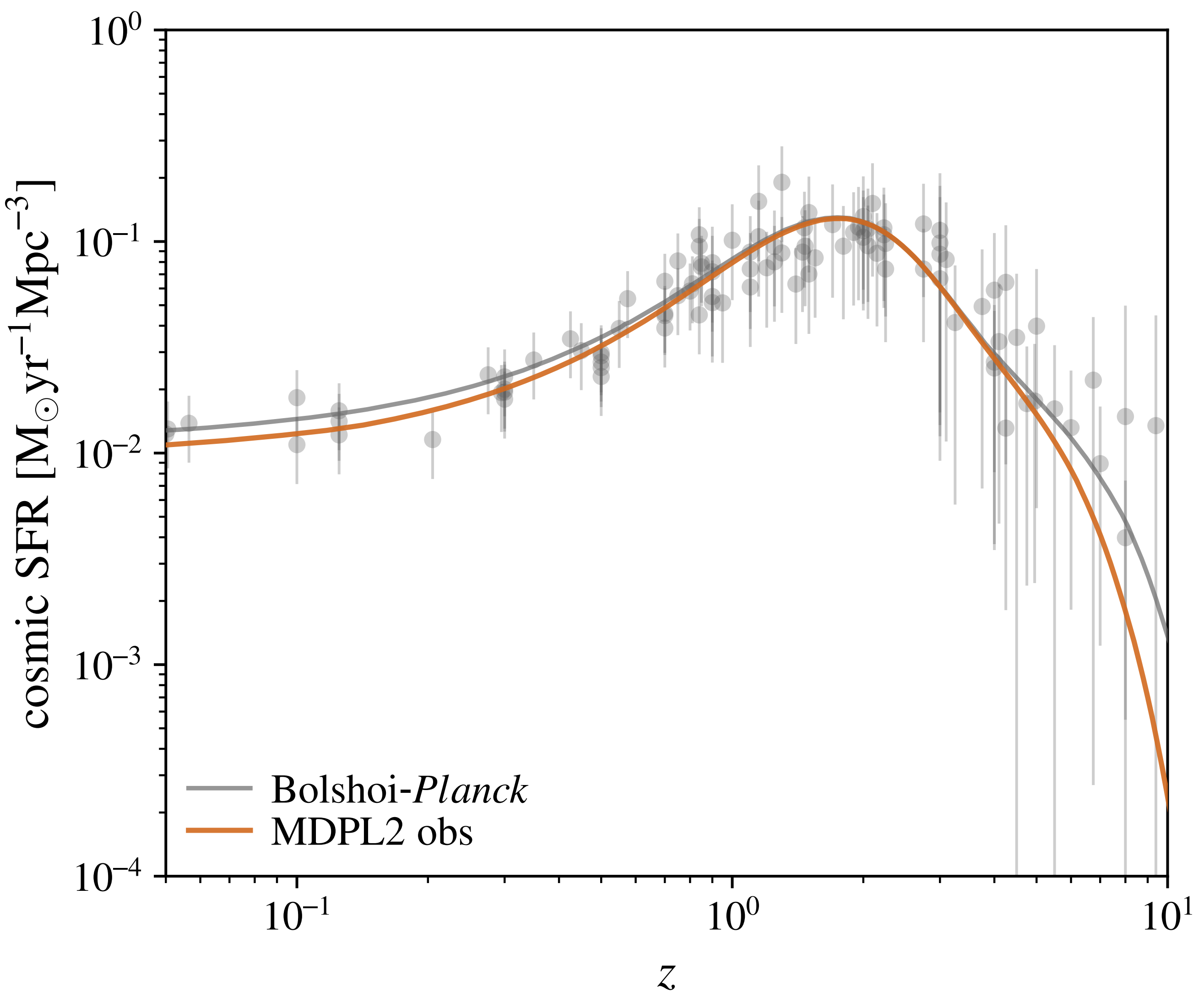


Implementation: CIB

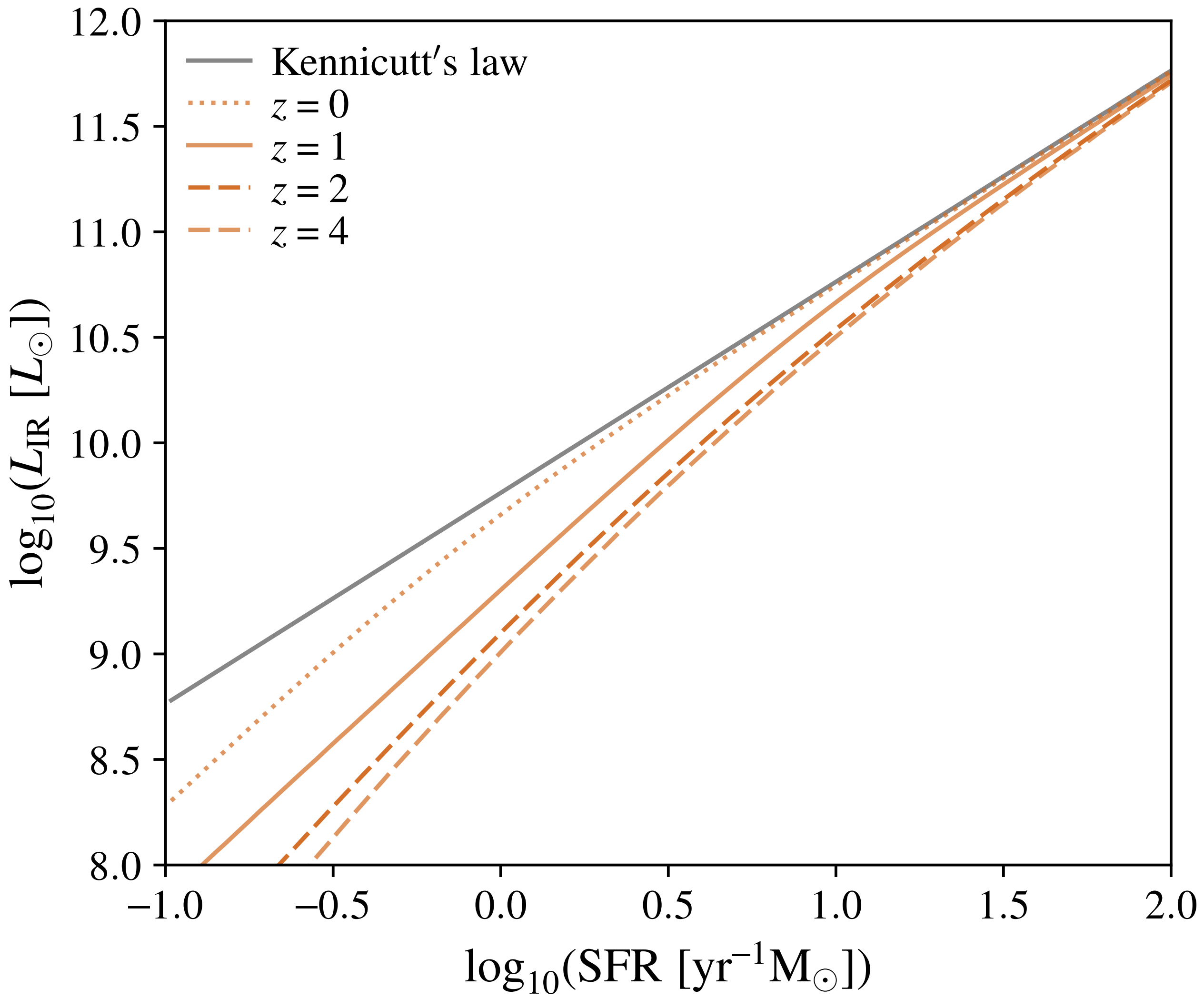
1. Start from Rockstar halos.

2. Apply UniverseMachine (get M_{*}/SFR).



Implementation: CIB

1. Start from Rockstar halos.
2. Apply UniverseMachine (get M_*/SFR).
3. Apply Kennicutts' law (get L_{IR}).



$$L_{\mathrm{IR}} = \frac{\mathrm{SFR}}{K_{\mathrm{IR}} + K_{\mathrm{UV}} 10^{-\mathrm{IRX}(M_*)}}$$

$$\log_{10}\mathrm{IRX} = 1.37 \times \log_{10}\left(\frac{M_*}{10^{9.63}}\right)$$

(Bouwens2020)

Implementation: CIB

1. Start from Rockstar halos.

2. Apply UniverseMachine (get M_*/SFR).

3. Apply Kennicutts' law (get L_{IR}).

4. Use empirical fitting relations to obtain M_{dust} and T_{dust}.

(Donevski2020)

$$\frac{M_{dust}}{M_*} = \frac{M_{mol}}{M_*} \times Z_{gas}$$

(Tacconi2020)

$$\frac{M_{mol}}{M_*} = A + B \times (\log(1+z))^2 + D \times \log_{10}(M_* - 10.7)$$

(Hunt2016)

$$Z_{gas} = -0.14\log_{10}(SFR) + 0.37\log_{10}(M_*) + 4.82$$

↓

= Free parameters

$$T_d = A_d \left(\frac{L_{IR}}{M_{dust}}\right)^{1/(4+\beta_d)} \qquad \beta_d = \frac{\zeta_d \times a}{b + c \times T_d}$$

Implementation: CIB

1. Start from Rockstar halos.
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3. Apply Kennicutts' law (get L_{IR}).
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5. Compute SED for individual sources

(Donevski2020)

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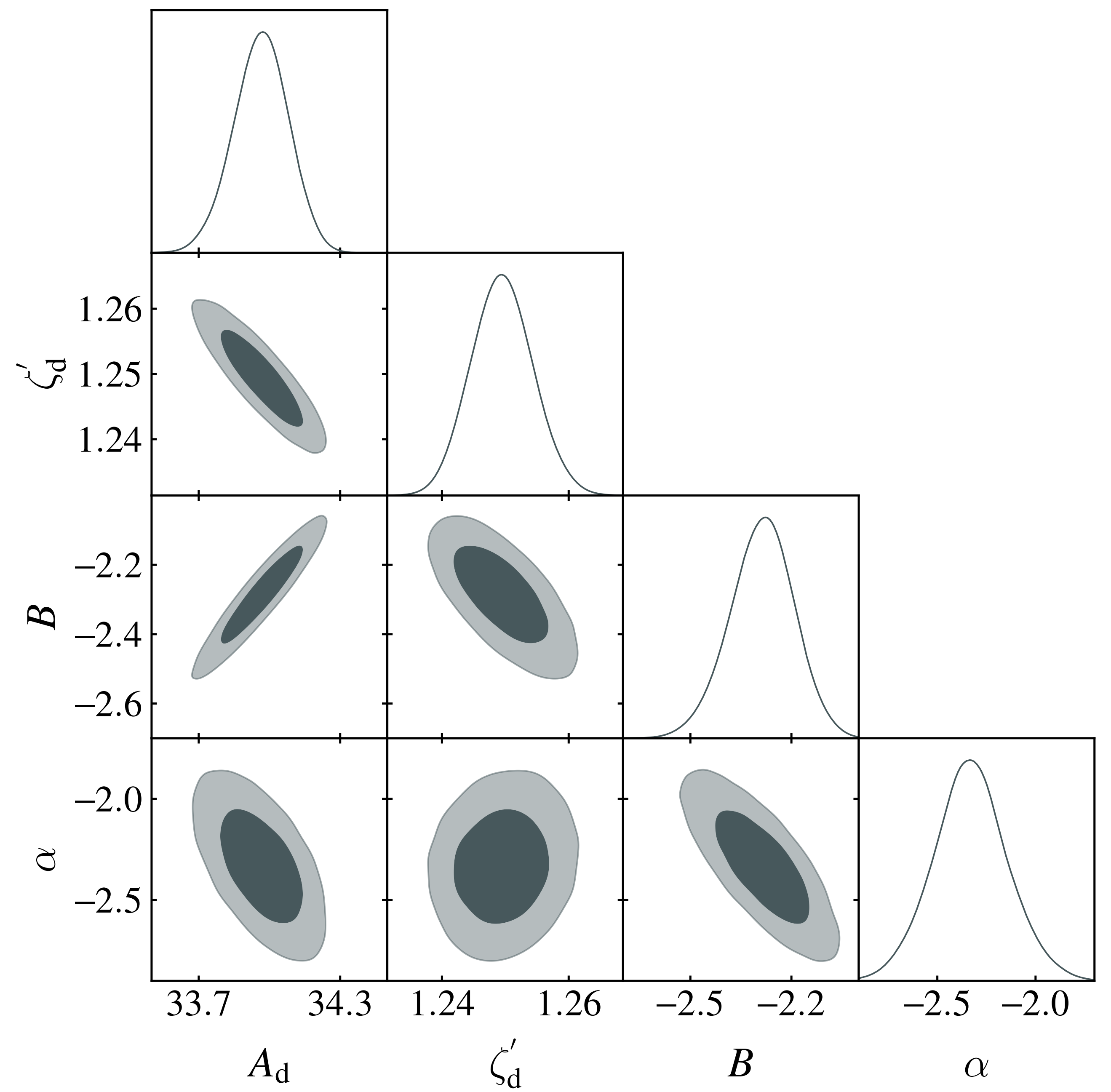
= Free parameters

$$T_d = A_d \left(\frac{L_{IR}}{M_{dust}}\right)^{1/(4+\beta_d)} \qquad \beta_d = \frac{\zeta_d \times a}{b + c \times T_d}$$

$$\Phi(\nu, T_d) = \begin{cases} \left[\exp(\frac{h\nu}{kT_d}) - 1\right]^{-1} \nu^{\beta_d+3}, & (\nu \le \nu') \\ \left[\exp(\frac{h\nu'}{kT_d}) - 1\right]^{-1} \nu'^{\beta_d+3} \left(\frac{\nu}{\nu'}\right)^{-\alpha_d}, & (\nu > \nu') \end{cases}$$

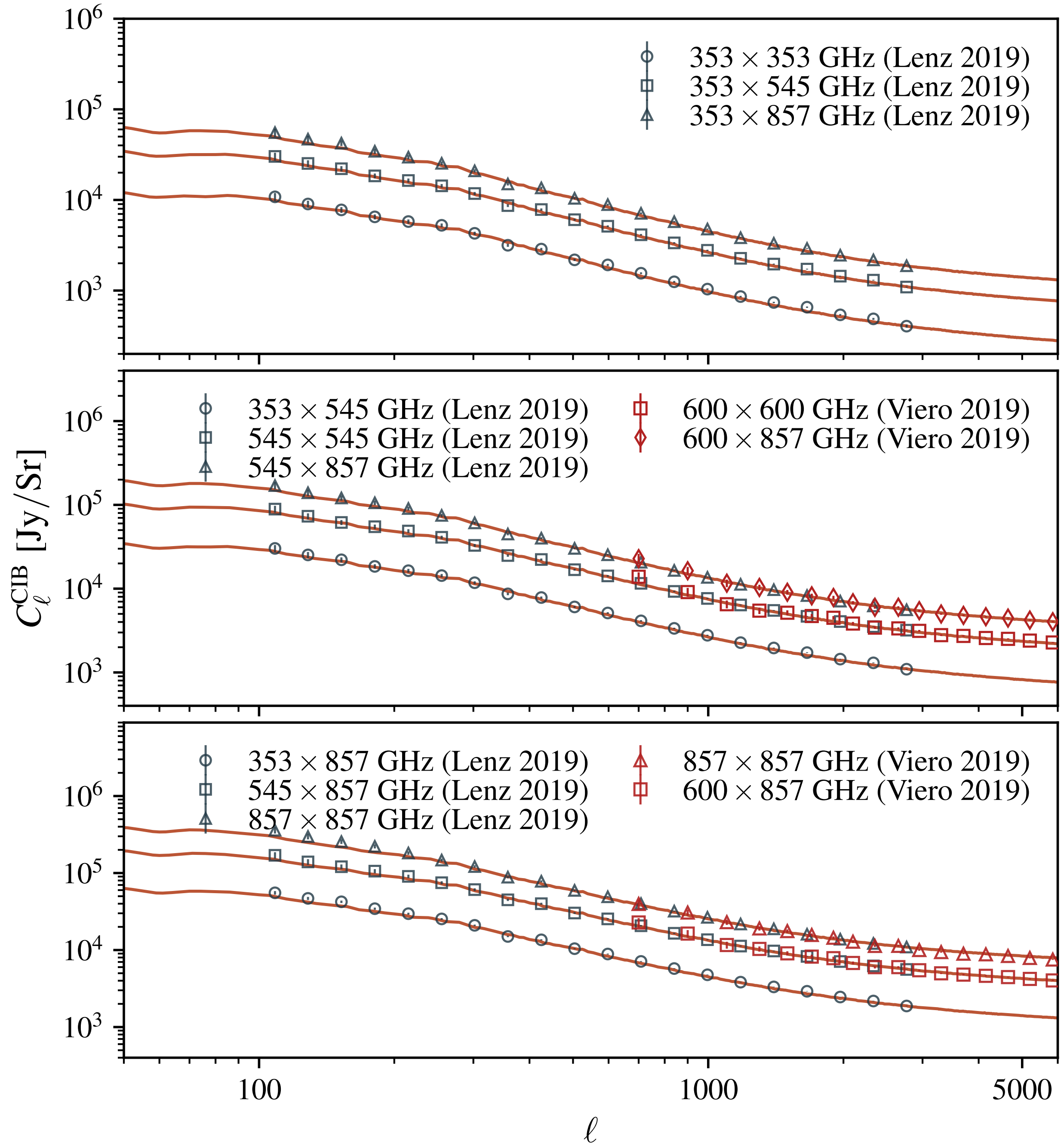
Implementation: CIB

1. Start from Rockstar halos.
2. Apply UniverseMachine (get M_*/SFR).
3. Apply Kennicutts' law (get $L_{\rm IR}$).
4. Use empirical fitting relations to obtain $M_{\rm dust}$ and $T_{\rm dust}$.
5. Compute SED for individual sources
6. Generate a CIB power spectrum emulator.
7. Run MCMC to get best-fit parameters that match with Lenz2019 CIB maps.

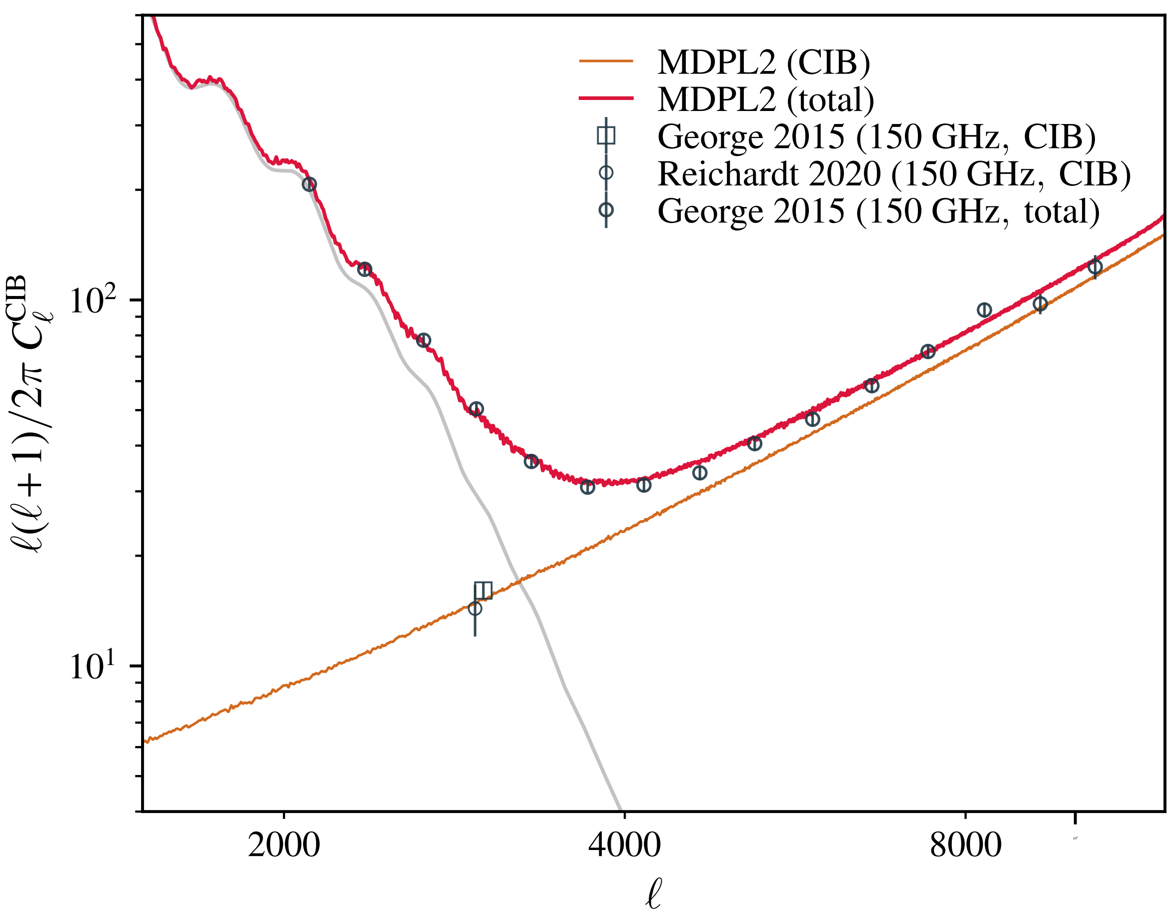


Implementation: CIB

CIB auto-spectrum at *Planck/Herchel* frequencies

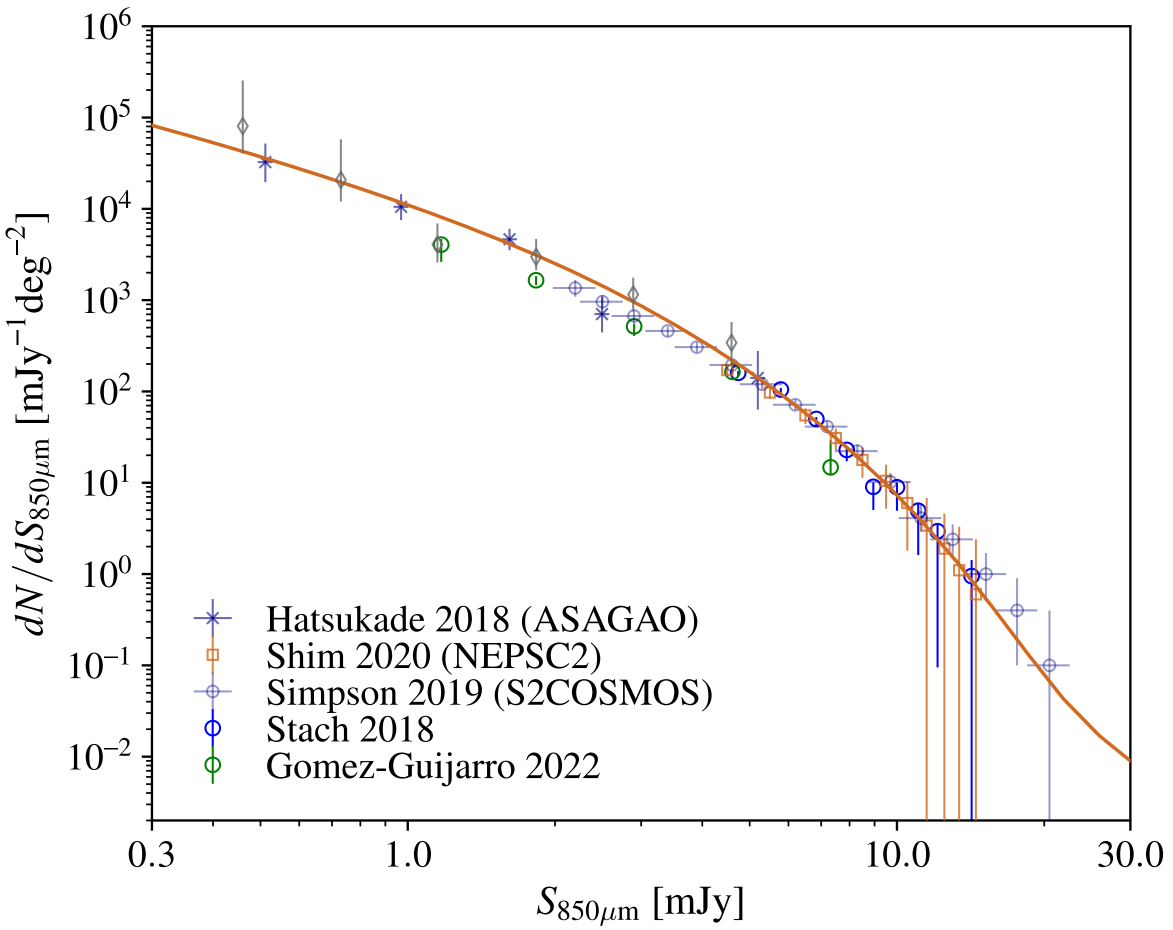


CIB auto-spectrum at SPT 150 GHz

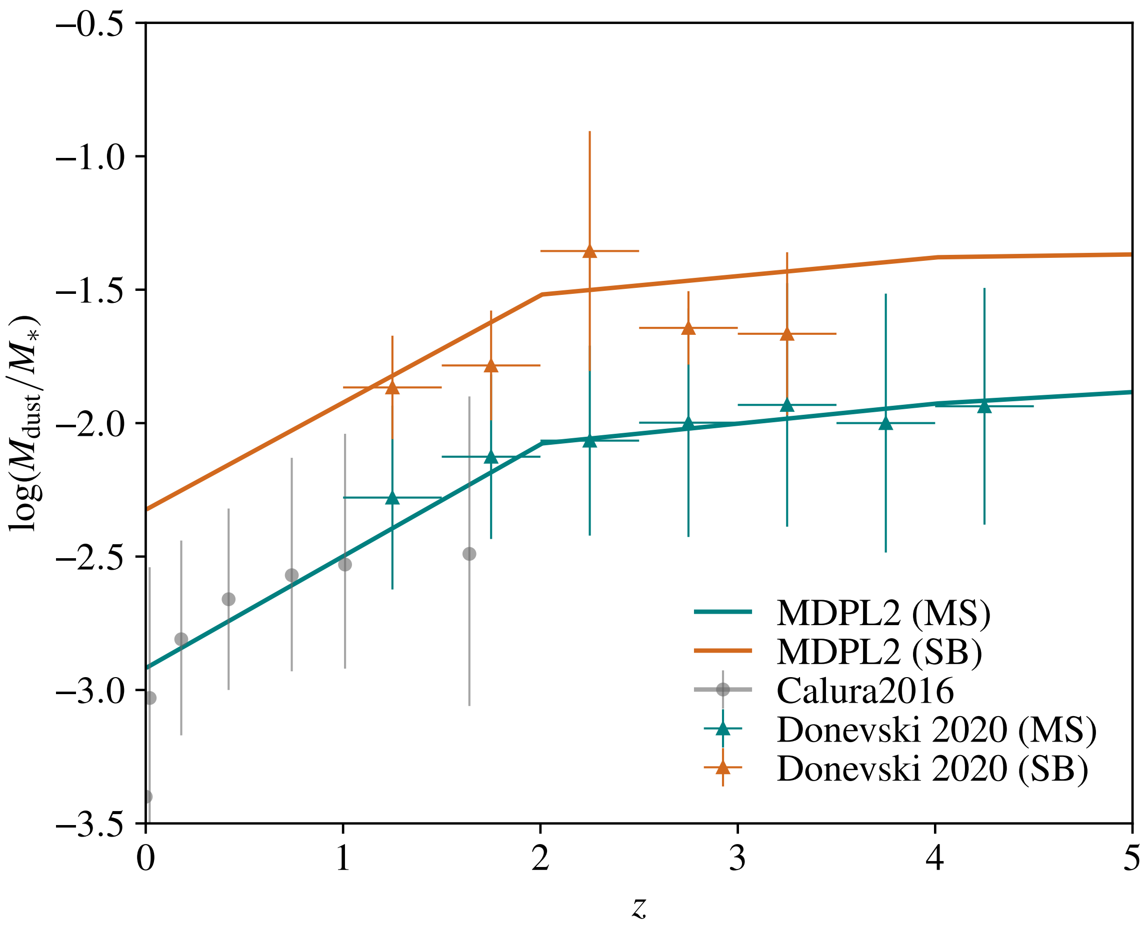


Implementation: CIB

IR source differential number counts

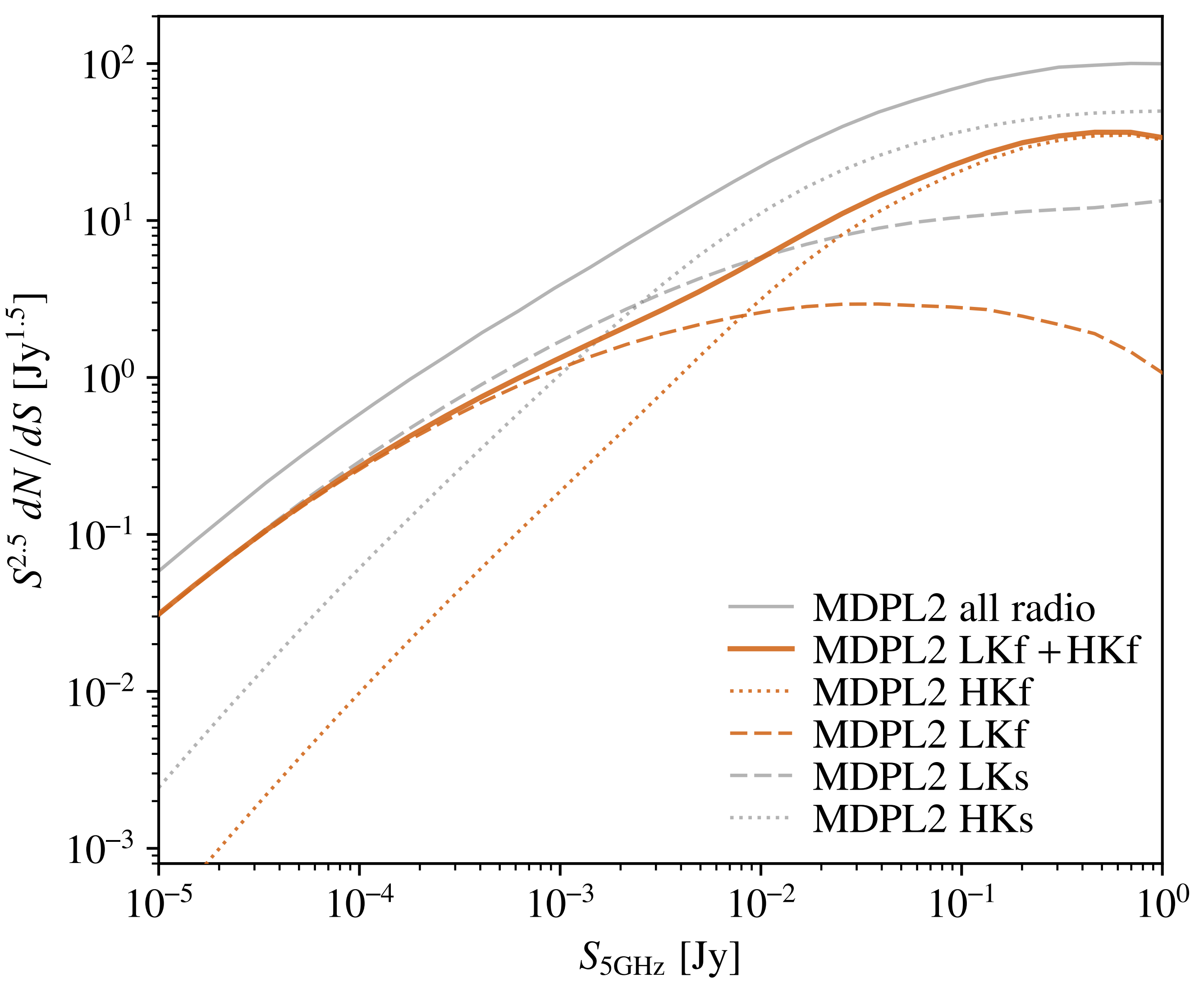


$M_{\rm dust}/M_*$ evolution



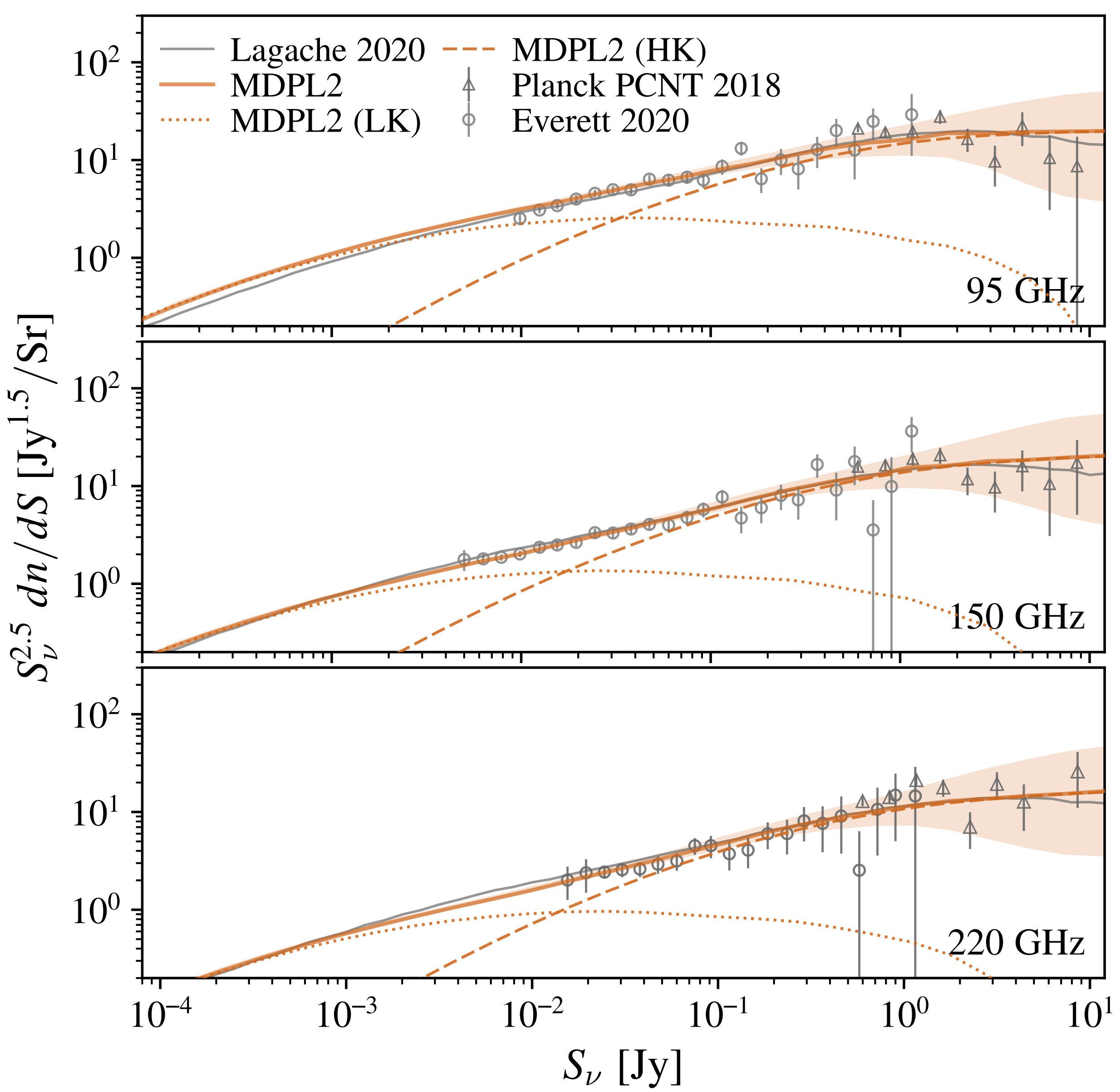
Implementation: Radio

1. Start from Rockstar halos.
2. Apply UniverseMachine (get M_*/SFR).
3. Apply results from TRINITY (to get $M_{\rm BH}$ and fraction of AGNs).
4. Do abundance matching with 5GHz luminosity function from Tucci2021.
5. Scale the frequency up to match with 150 GHz.
6. Scale frequency to 90 and 220 GHz using α_{150}^{90} and α_{150}^{220} derived from data.

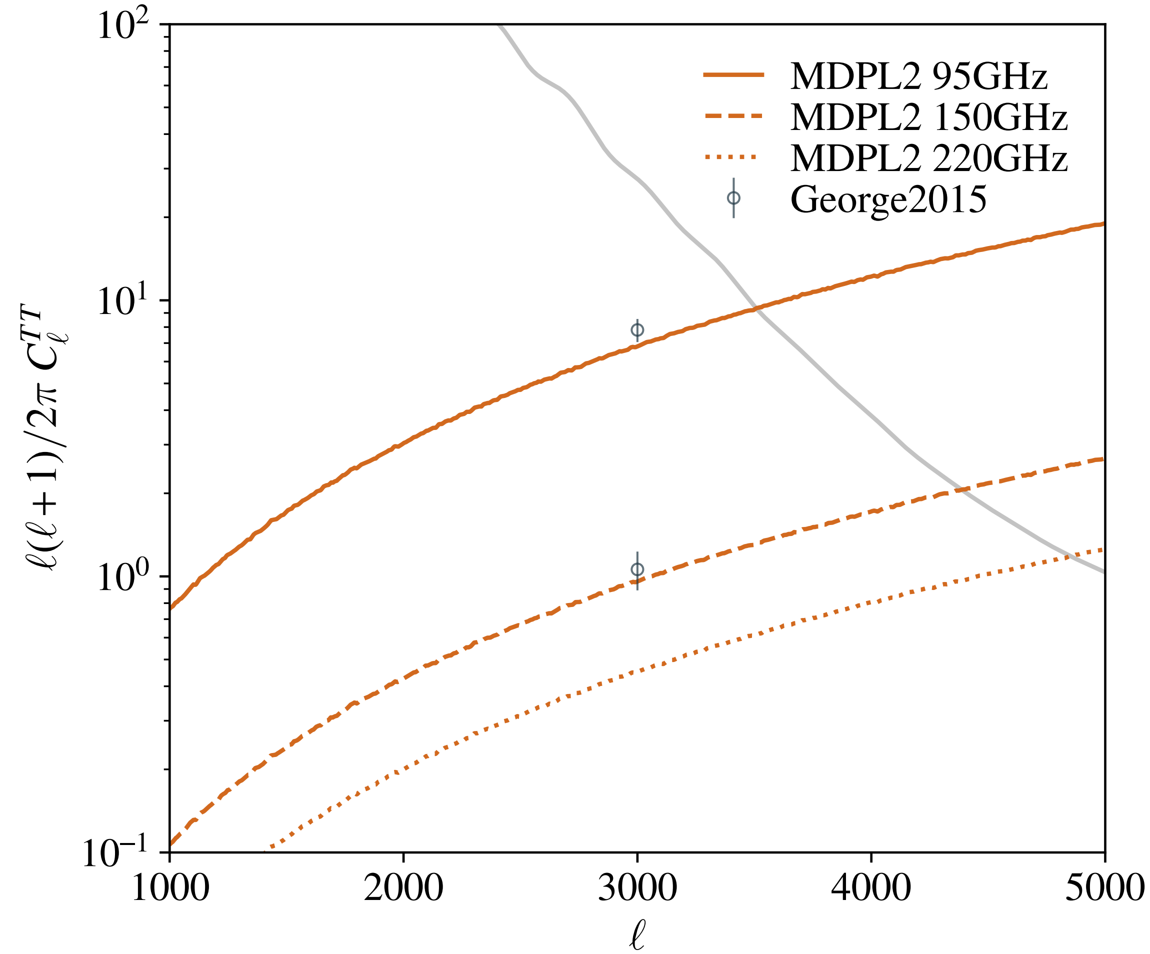


Validation: Radio source counts and power spectra

Radio source differential number counts



Radio source power spectra



Power spectra

Total 90 GHz map = CMB + kSZ + CIB_{90GHz} + tSZ_{90GHz} + $radio_{90GHz}$

Power spectra

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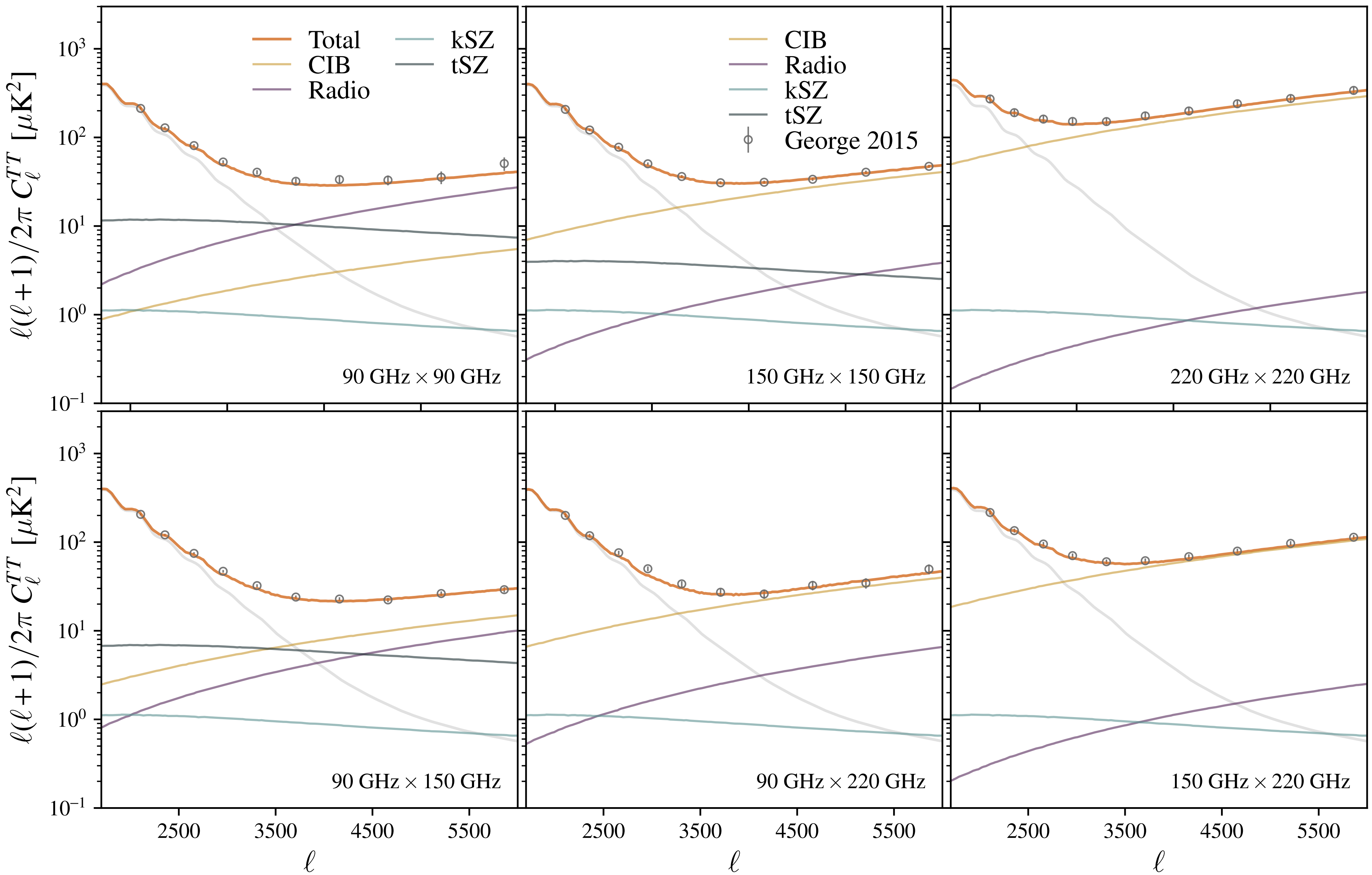
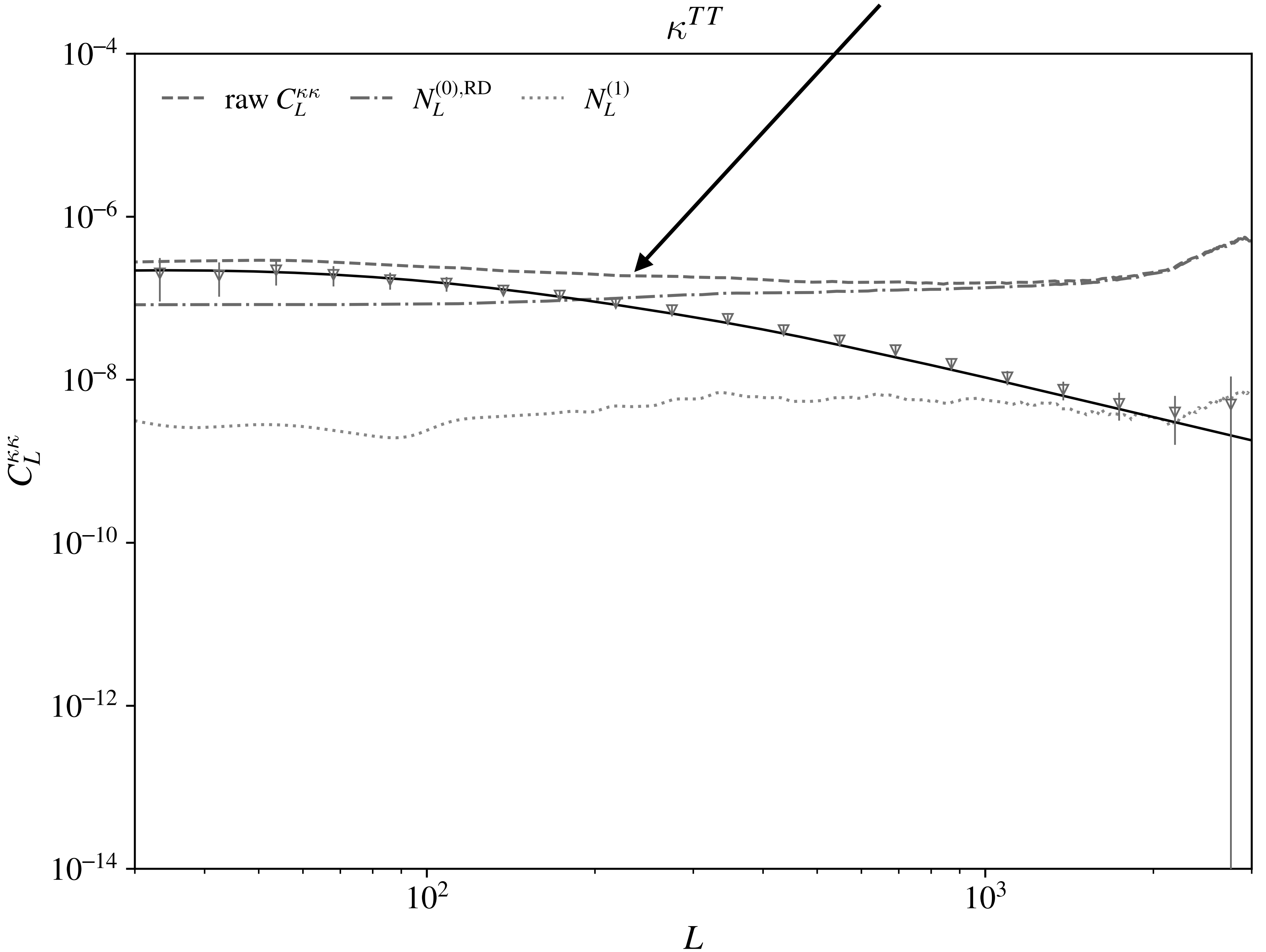


Example usage of MDPL2

1. Biases in reconstructed CMB lensing map
2. Biases in reconstructed tSZ maps
3. Multi-tracer delensing forecasting

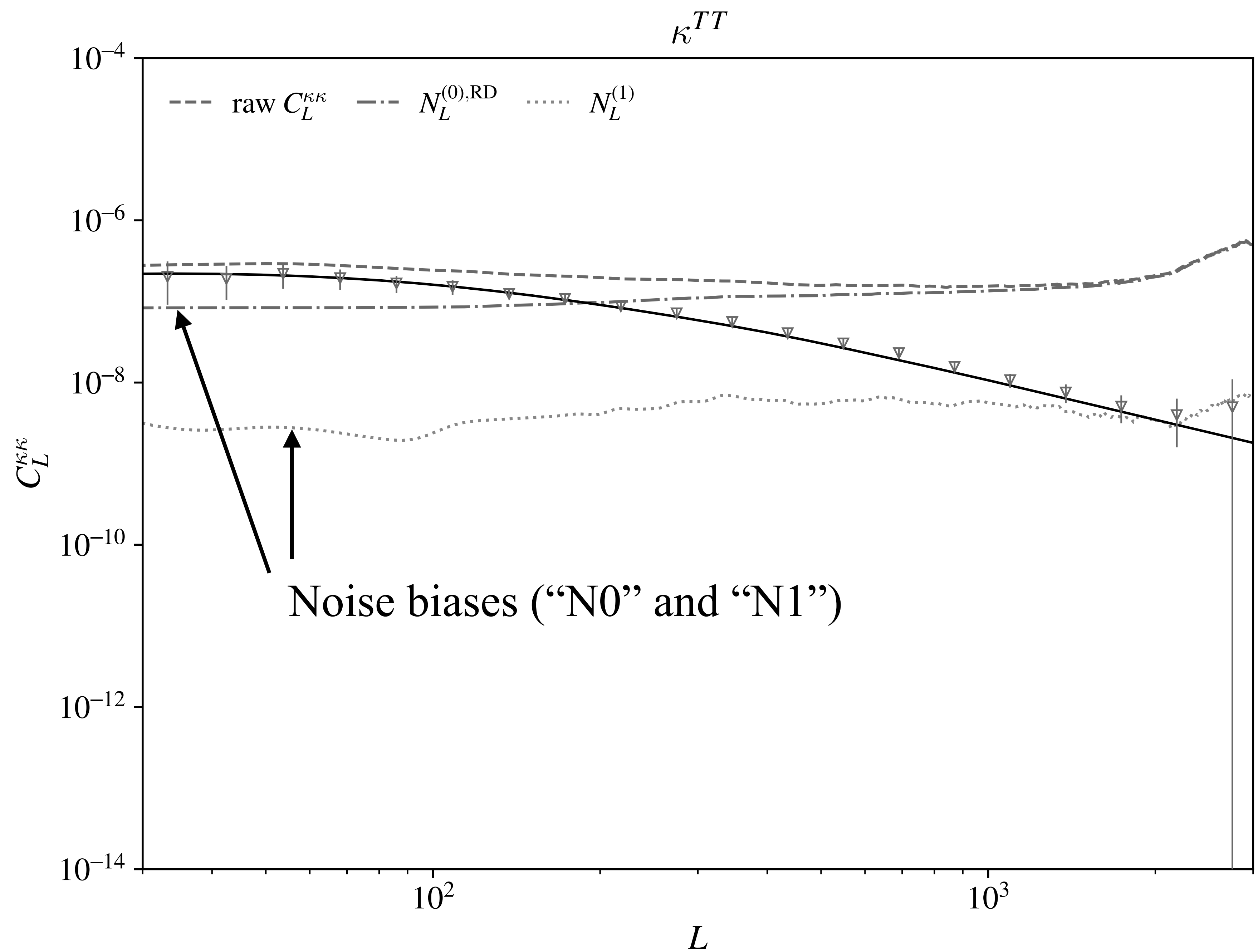
Biases in CMB lensing maps

Raw CMB lensing spectrum



Setup: 5μK-arcmin experiment, masking ptsrcs down to 6 mJy, clusters down to $2 \times 10^{14} M_\odot$

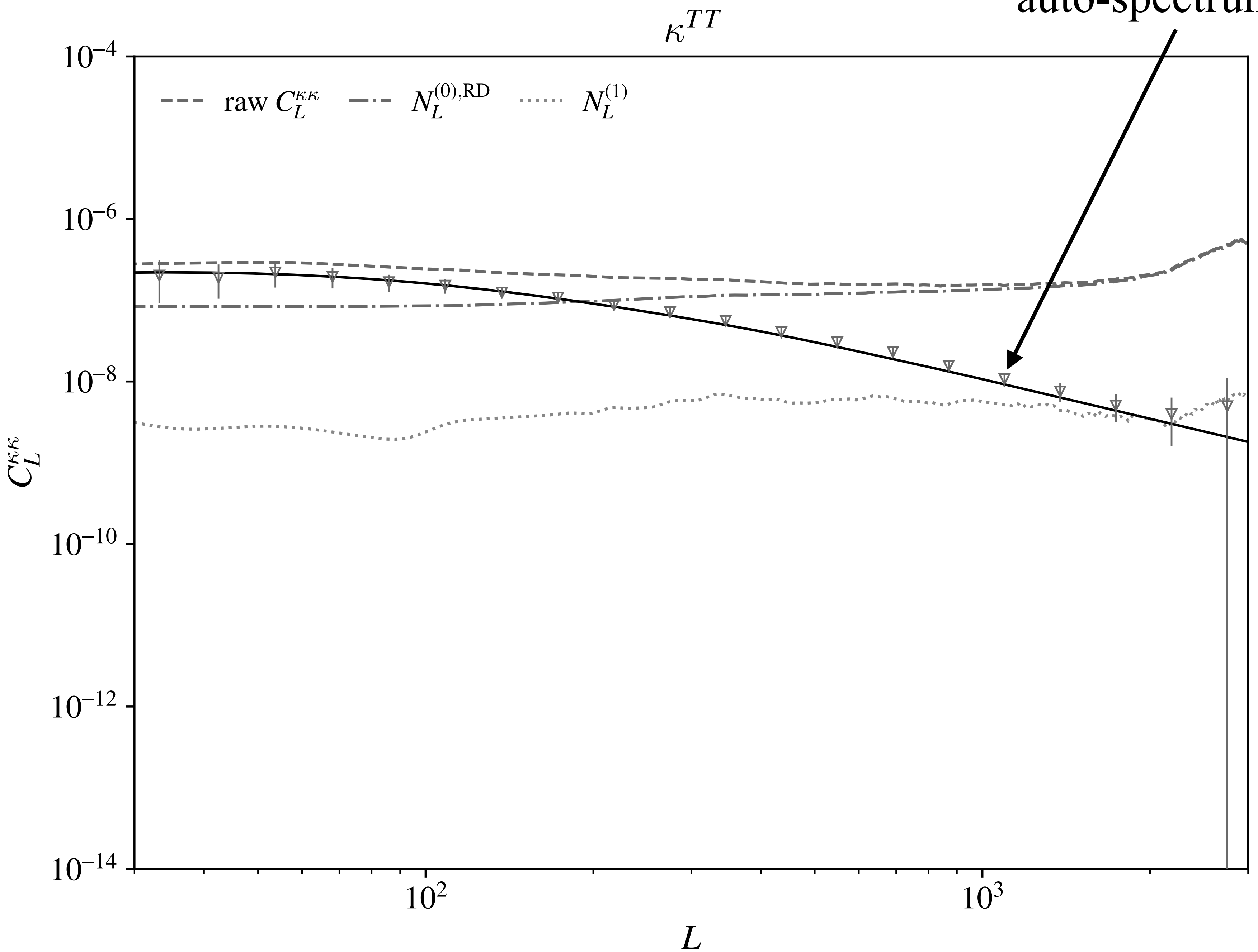
Biases in CMB lensing maps



Setup: 5μK-arcmin experiment, masking ptsrcs down to 6 mJy, clusters down to $2 \times 10^{14} M_\odot$

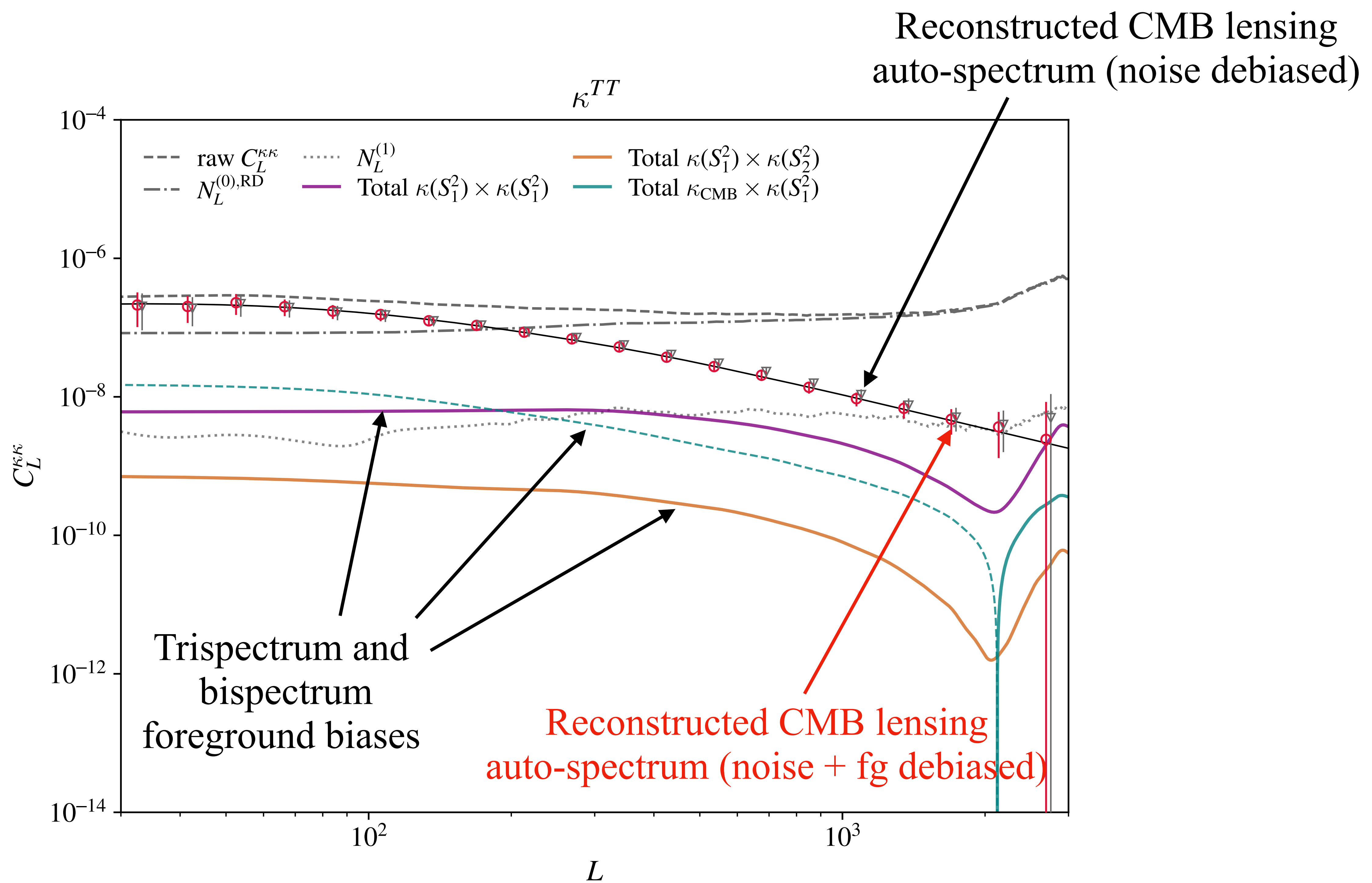
Biases in CMB lensing maps

Reconstructed CMB lensing auto-spectrum (noise debiased)



Setup: 5μK-arcmin experiment, masking ptsrcs down to 6 mJy, clusters down to $2 \times 10^{14} M_\odot$

Biases in CMB lensing maps



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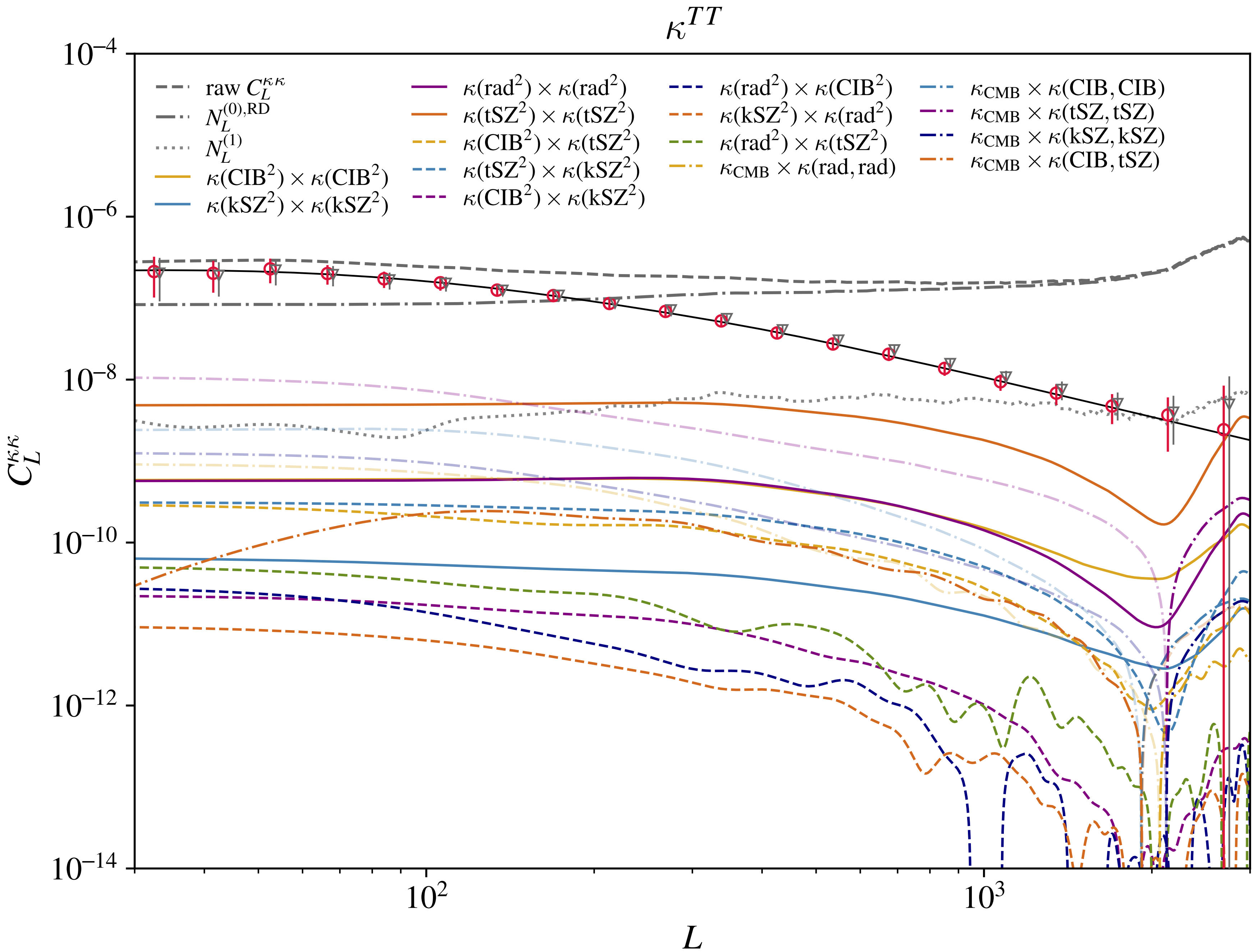
Biases in CMB lensing maps



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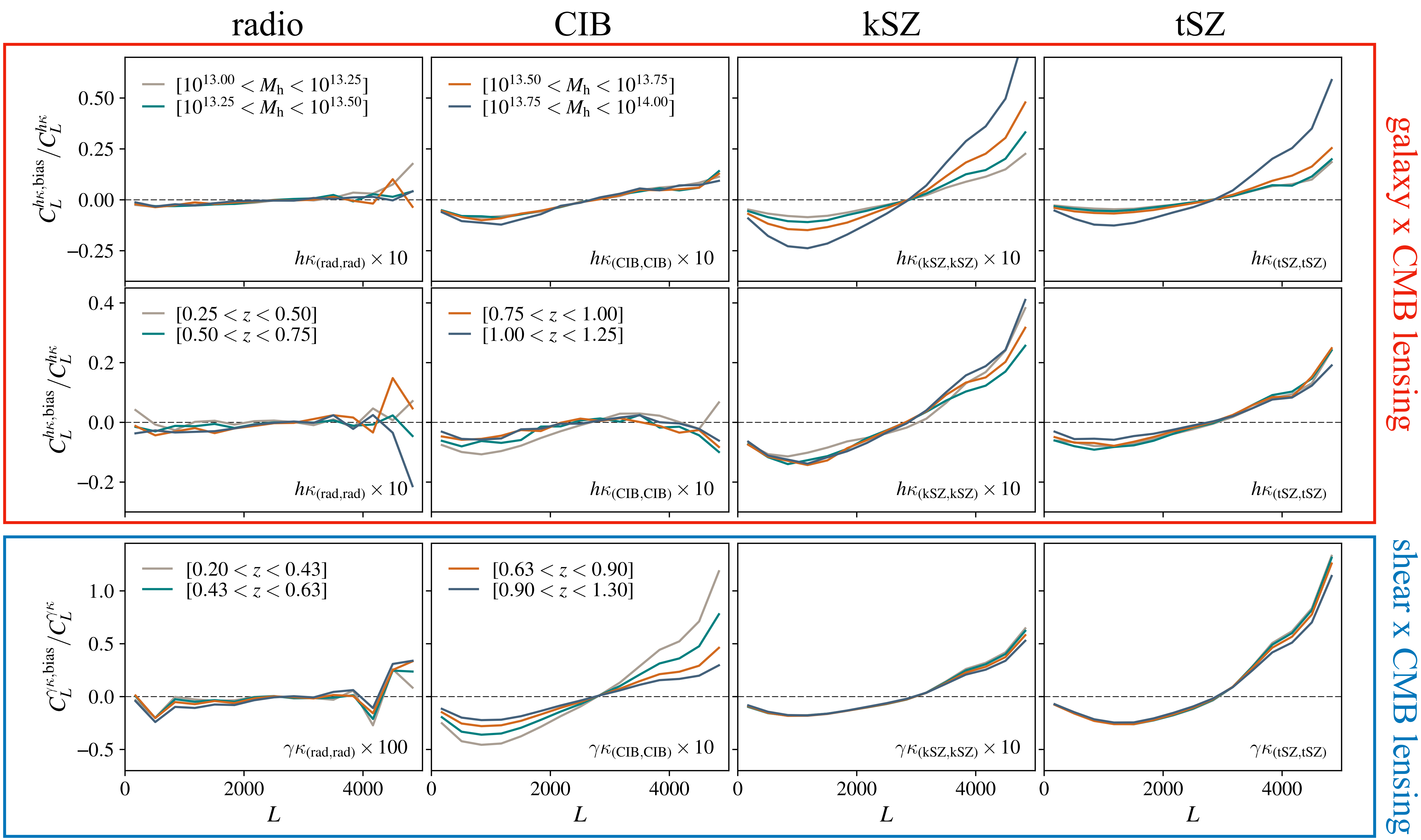
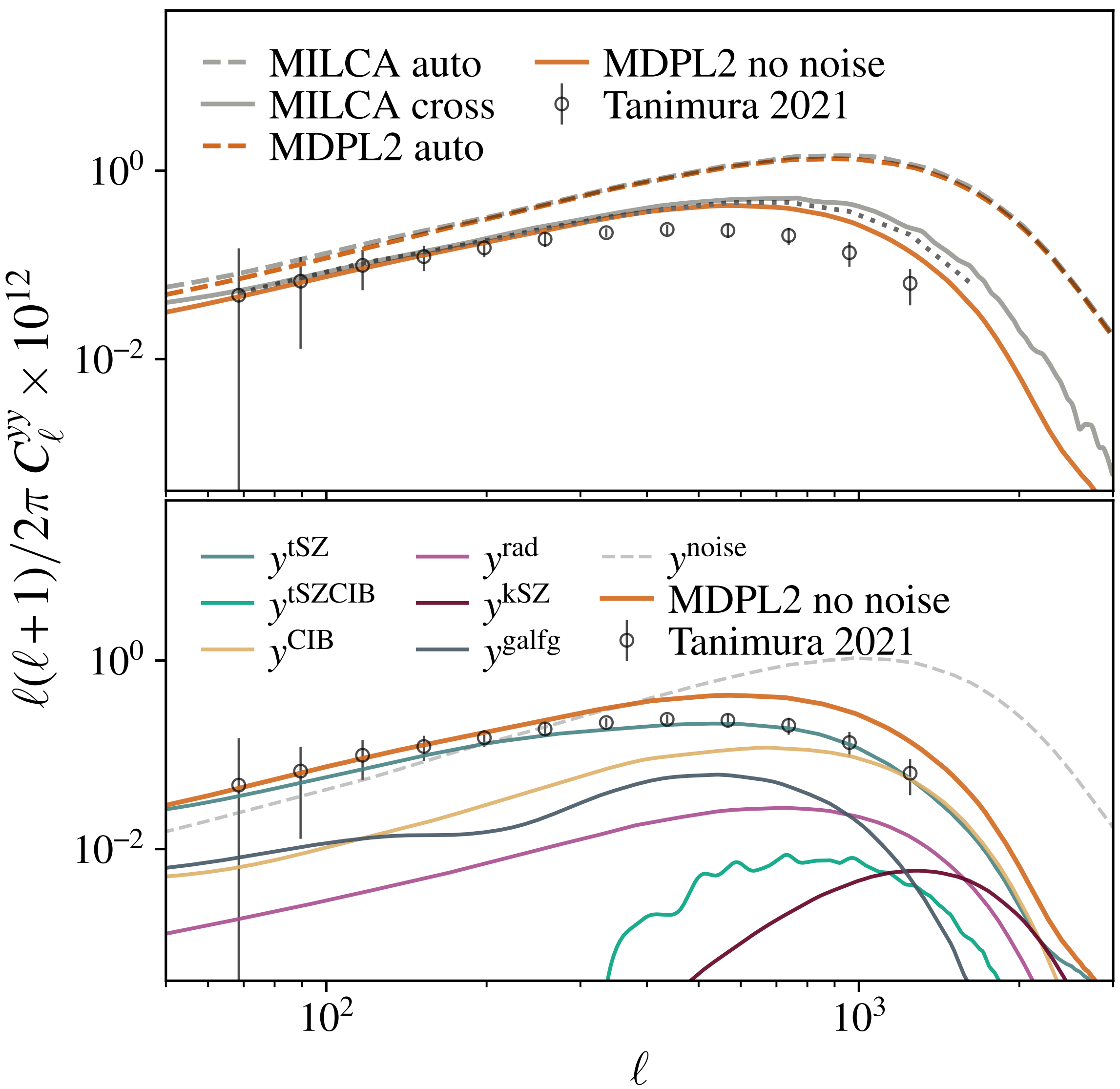
Biases in CMB lensing maps

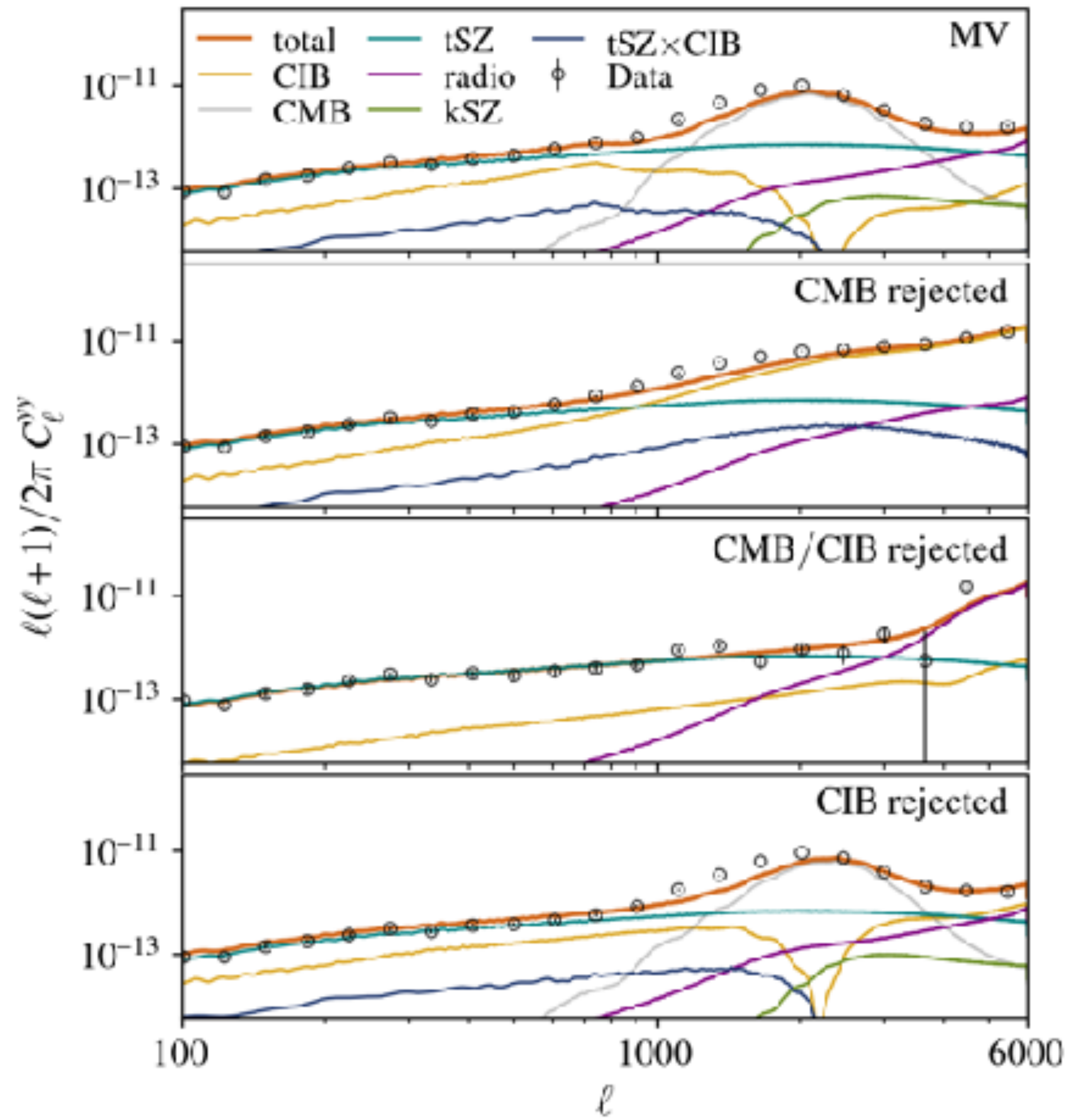


**Slightly different setup from the previous slide

Biases in tSZ maps

Can also pass frequency maps through *Planck* MILCA/SPT *y*map making pipeline, and investigate biases in those maps.

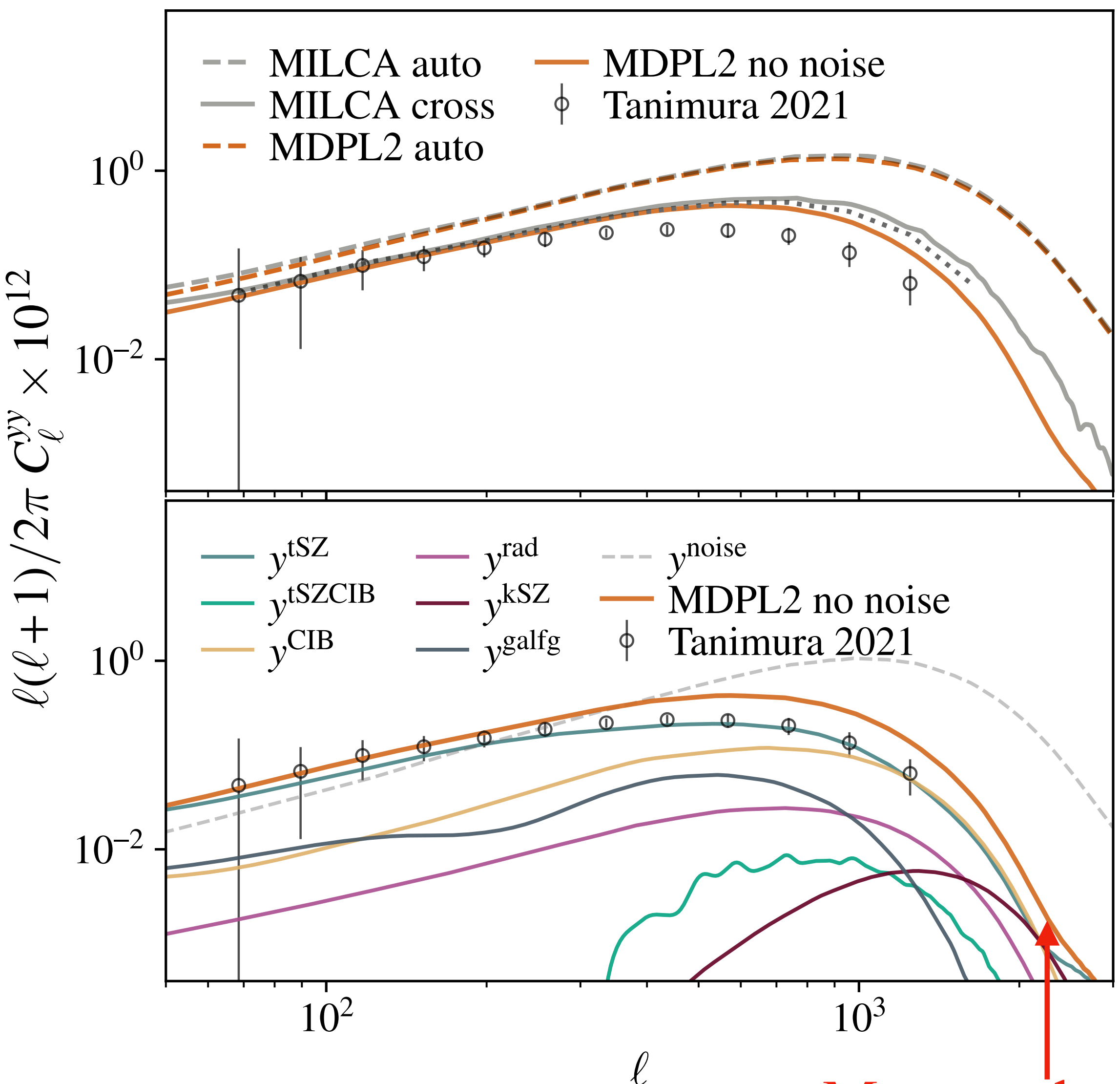


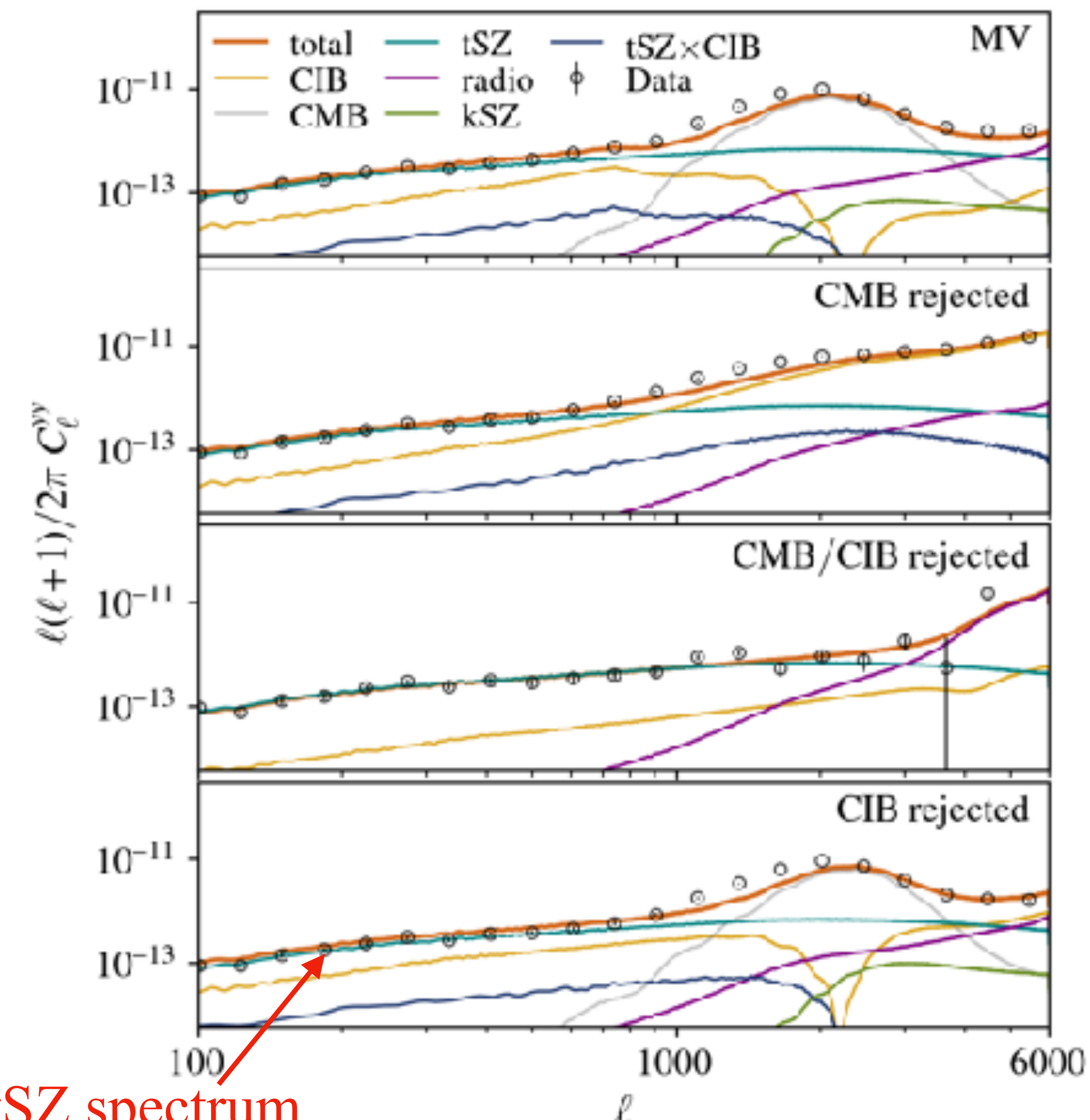


We can understand which foreground components are responsible for the various "features" in the power spectrum.

Biases in tSZ maps

Can also pass frequency maps through *Planck* MILCA/SPT *y*map making pipeline, and investigate biases in those maps.





Measured total tSZ spectrum

We can understand which foreground components are responsible for the various "features" in the power spectrum.

Biases in tSZ maps

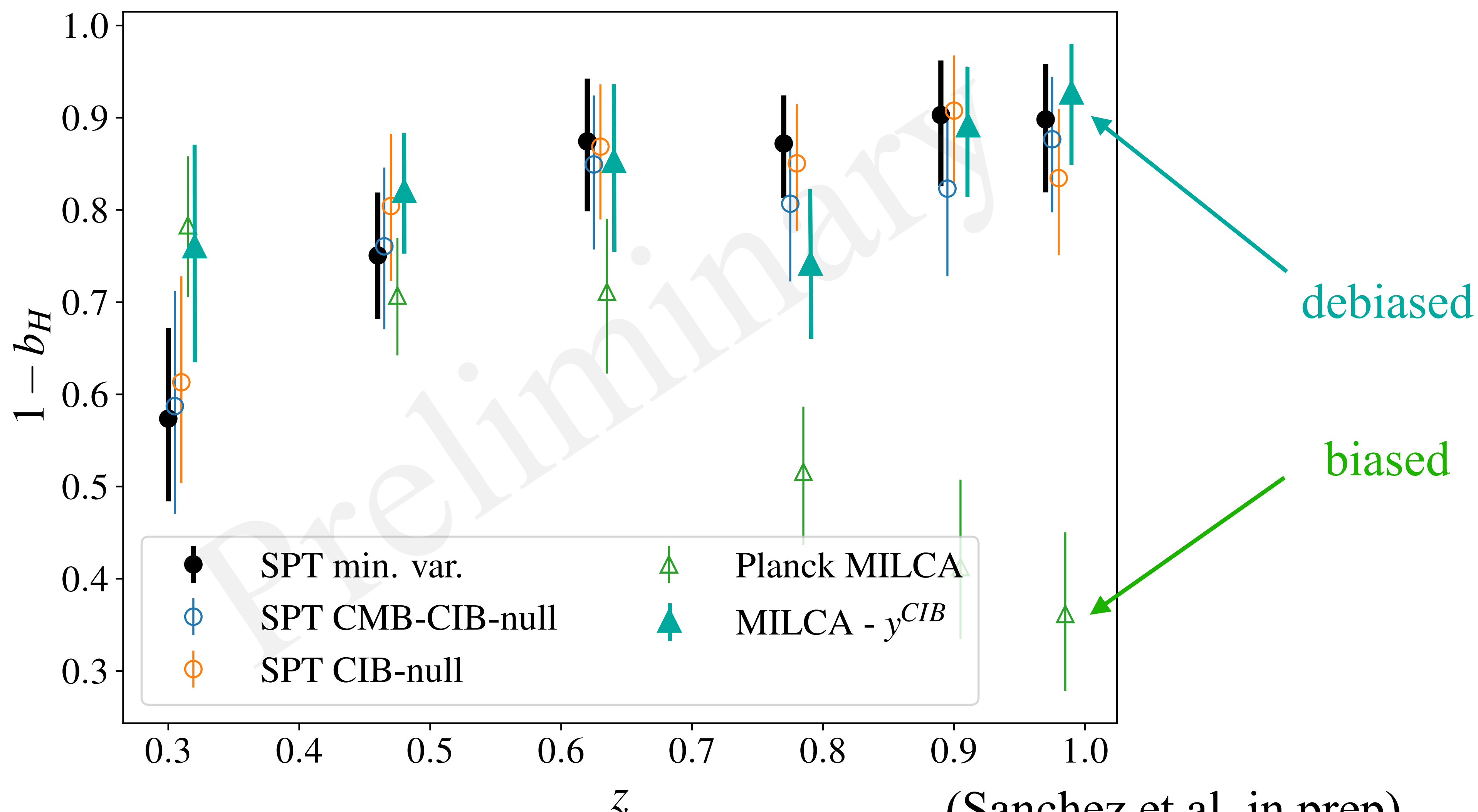
We can identify biases in cross-correlations and estimate the bias using the combination of data simulations.

Specially for MILCA, we find that there is a lot of CIB contamination in tSZ × galaxies correlation.

$$P_e(r) = P_* \times p(r/r_{500c})$$

$$p(x) = (c_P x)^{-\gamma}\left[1 + (c_P x)^{\alpha}\right]^{\frac{\gamma-\beta}{\alpha}}$$

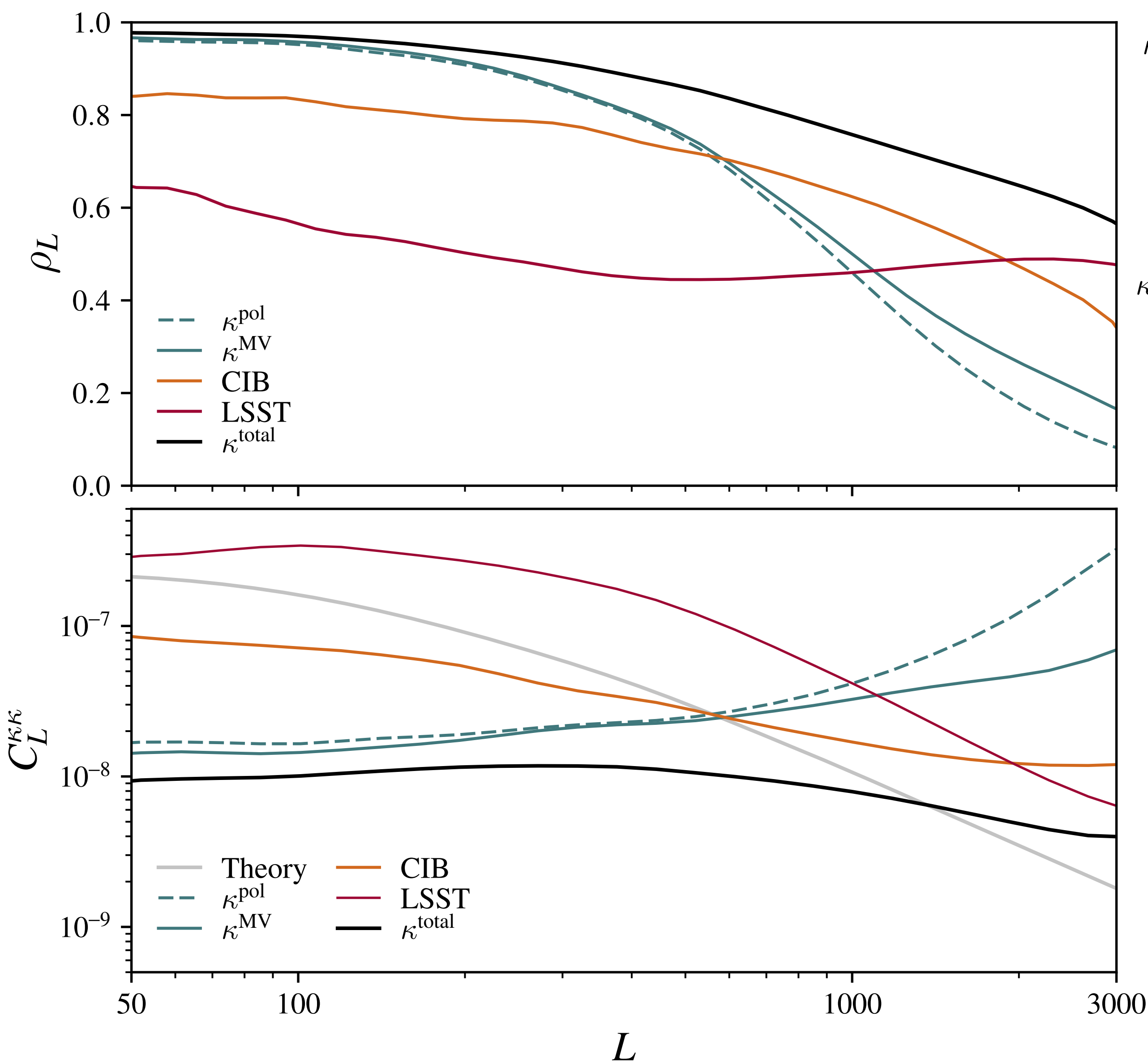
$$P_* = P_0 \left(1.65\,\mathrm{eV\,cm^{-3}}\right) h_{70}^{8/3} \left(\frac{h_{70}(1-b_H)M_{500c}}{3\times 10^{14} M_\odot}\right)^{0.79}$$



(Sanchez et al. in prep)

Multi-tracer delensing forecasting

One of the key science for Stage-3 and Stage-4 CMB experiments is to constraint *r,* and we want maximize the delensing efficiency by throwing every possible data to improve our estimate of the lensing potential. → Combine internal lensing + CIB + LSS



$\ell = 1500$

	$\kappa_{\rm CMB}$	$\kappa^{TT}_{\rm CMB}$	$\kappa^{TT,\rm db}_{\rm CMB}$	$\kappa^{TT}_{\rm CIB}$	$\kappa^{\rm MV}_{\rm CMB}$	$\kappa^{\rm MV,db}_{\rm CMB}$	$\kappa^{\rm MV}_{\rm CIB}$	$\kappa^{EE+EB}_{\rm CMB}$	$\kappa^{\rm CIB}$	$\kappa^{\rm LSST}$	$\kappa^{EE+EB+\rm CIB}$	$\kappa^{EE+EB+\rm CIB+LSST}$	$\kappa^{\rm MV+CIB}$	$\kappa^{\rm MV,db+CIB}$	$\kappa^{\rm MV+CIB+LSST}$	$\kappa^{\rm MV,db+CIB+LSST}$
$\kappa^{\rm MV,db+CIB+LSST}$	0.69	0.41	0.42	−0.10	0.52	0.52	−0.10	0.35	0.77	0.70	0.97	0.97	0.85	0.85	1.00	1.00
$\kappa^{\rm MV+CIB+LSST}$	0.69	0.41	0.41	−0.09	0.52	0.52	−0.09	0.35	0.77	0.70	0.97	0.97	0.85	0.85	1.00	1.00
$\kappa^{\rm MV,db+CIB}$	0.60	0.49	0.50	−0.12	0.59	0.60	−0.12	0.37	0.91	0.23	0.80	0.80	1.00	1.00	0.86	0.86
$\kappa^{\rm MV+CIB}$	0.59	0.50	0.50	−0.10	0.59	0.60	−0.10	0.37	0.91	0.23	0.80	0.80	1.00	1.00	0.86	0.86
$\kappa^{EE+EB+\rm CIB+LSST}$	0.68	0.18	0.19	−0.10	0.37	0.38	−0.10	0.43	0.78	0.71	1.00	1.00	0.81	0.81	0.97	0.97
$\kappa^{EE+EB+\rm CIB}$	0.68	0.18	0.19	−0.10	0.37	0.38	−0.10	0.43	0.78	0.71	1.00	1.00	0.81	0.81	0.97	0.97
$\kappa^{\rm LSST}$	0.48	0.09	0.09	−0.03	0.15	0.15	−0.03	0.15	0.20	1.00	0.71	0.71	0.24	0.24	0.70	0.70
$\kappa^{\rm CIB}$	0.54	0.17	0.18	−0.13	0.21	0.21	−0.13	0.14	1.00	0.22	0.79	0.79	0.91	0.91	0.78	0.78
$\kappa^{EE+EB}_{\rm CMB}$	0.29	0.10	0.10	−0.02	0.61	0.61	−0.02	1.00	0.16	0.15	0.44	0.44	0.38	0.38	0.36	0.36
$\kappa^{\rm MV}_{\rm CIB}$	−0.08	0.02	−0.03	1.00	0.01	−0.03	1.00	−0.02	−0.15	−0.04	−0.13	−0.13	−0.12	−0.14	−0.11	−0.12
$\kappa^{\rm MV,db}_{\rm CMB}$	0.36	0.84	0.84	−0.03	1.00	1.00	−0.03	0.61	0.23	0.15	0.38	0.38	0.60	0.60	0.53	0.53
$\kappa^{\rm MV}_{\rm CMB}$	0.36	0.84	0.84	0.01	1.00	1.00	0.01	0.61	0.22	0.15	0.38	0.38	0.60	0.60	0.52	0.52
$\kappa^{TT}_{\rm CIB}$	−0.08	0.02	−0.03	1.00	0.01	−0.03	1.00	−0.02	−0.15	−0.04	−0.13	−0.13	−0.12	−0.14	−0.11	−0.12
$\kappa^{TT,\rm db}_{\rm CMB}$	0.27	1.00	1.00	−0.03	0.84	0.84	−0.03	0.10	0.18	0.09	0.19	0.19	0.50	0.50	0.42	0.42
$\kappa^{TT}_{\rm CMB}$	0.26	1.00	1.00	0.02	0.84	0.84	0.02	0.10	0.17	0.09	0.18	0.18	0.49	0.49	0.41	0.41
$\kappa_{\rm CMB}$	1.00	0.26	0.27	−0.08	0.36	0.36	−0.08	0.29	0.58	0.49	0.71	0.71	0.62	0.62	0.72	0.72

Part II summary

- MDPL2 synthetic sky simulation is one of the few simulations that have both CMB and LSS simulation products, tested to the level that is usable for real data analyses.
- The modelling is calibrated against existing observational data and external hydrodynamical simulations.
- It was built with a focus on accurate modelling of the CMB foregrounds, for the purpose of assessing biases in auto/cross-correlation measurements of SZ/lensing.
- MDPL2 is already being used for several analyses e.g. 6x2pt, galaxies $\times$ tSZ, shear $\times$ tSZ, pairwise kSZ, multi-tracer delensing forecasts etc.
- Future/On-going works:
    - Implementation of more realistic LSST galaxies
    - Baryonification
    - Learning from MDPL2 and pasting secondaries to cheaper mocks
    - LIM
    - Other observables (X-ray, clusters, patchy kSZ etc.)

End